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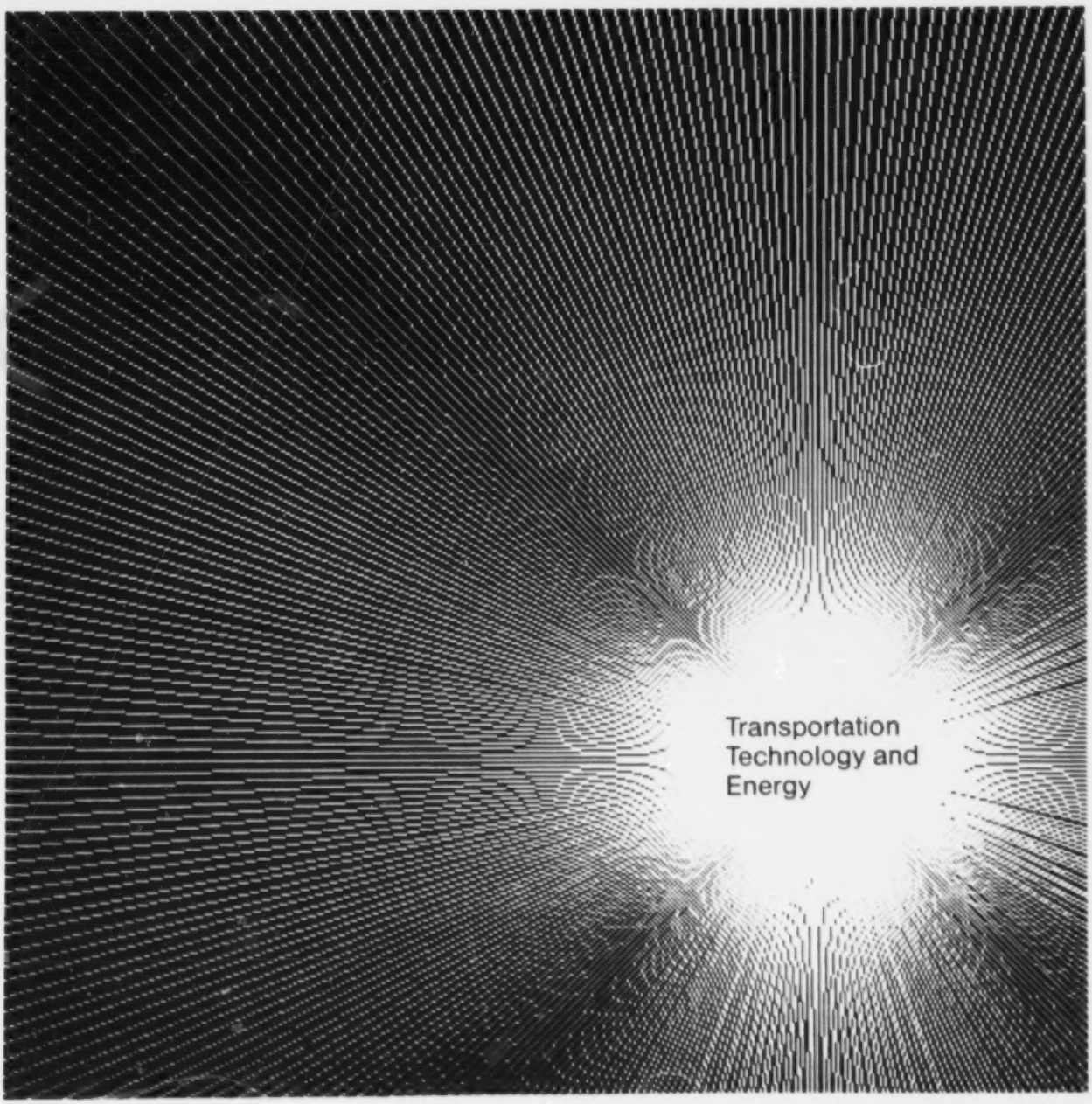
Active Vision Sensor Technology Applications – Final Report

TCT-85-01



TCT-85-01

Active Vision Sensor Technology Applications – Final Report

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Published by:
The Transit Control Technology and Systems Office
Transportation Technology and Energy Branch
Ontario Ministry of Transportation and Communications
Hon. Ed Fulton, Minister
John Barr, Deputy Minister

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Ministry of Transportation and Communications
1201 Wilson Avenue
Downsview, Ontario
Canada M3M 1J8
(416) 248-7226

August 1985

Technical Report Documentation Page

MTC Report Number TCT-85-01	ISBN Number:	Other Document Number:	Date: August 1985
Title: Active Vision Sensor Technology Applications -- Final Report			
Authors (name, title and/or organisation): A.K. Ghosh, et al, MPB Technologies Inc. J. Tsai, Project Manager, MTC			
Published by: The Transit Control Technology and Systems Office Transportation Technology and Energy Branch, MTC		**Client Group:**	
Participating Agencies:			

Abstract:
This report is a review of the state-of-the-art in active vision sensor technology and, in particular, microwave/millimetre wave radar sensors, laser radar sensors, and sonar sensors. Two main areas for application are assessed: object identification on the guideway, and guidance and control of stationary or moveable robots for inspection and cleaning.

Key Words: sensor, radar, laser, sonar, robotics, transit

Comments:

Distribution: on request

Copyright Status: Crown copyright

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EXECUTIVE SUMMARY

The objective of this study is to review the state-of-the-art in active vision sensor technology and, in particular, microwave/millimetre wave radar sensors, laser radar sensors and sonar sensors.

The two main application areas anticipated are

(a) object identification on the guideway,

(b) guidance and control of stationary or moveable robots for inspection and cleaning.

Possible Applications (Chapter 1)

Four possible application scenarios are considered in the area of guideway surveillance for object identifications.

(a) The sensor is mounted on the vehicle, looking forward along the track.

(b) A number of sensors are mounted along the guideway, each covering a section of track.

(c) Sensors cover level crossing.

(d) Sensors cover guideway in the station area.

For robot guidance and control, the applications are for

(a) inspection,

(b) cleaning.

Sonar technology (Chapter 2)

- This is limited to short range (~ 10 m).
- It is not suitable for vehicle-borne or along-the-guideway surveillance application.
- It may be suitable for robot guidance and control if the requirement is defined more precisely.
- More development is needed for high resolution sensor.

Microwave/millimetre wave radar technology (Chapter 3)

- Microwave radar is the most developed technology.
- Microwave Imaging developed for long distance is not suitable for the present application.
- Millimetre Wave imagery is still in its infancy.
- It is suitable for vehicle-mounted and along-the-guideway detection of objects (fairly small size).
- Identification of objects is a problem except for large targets (trucks).
- The range is 500 m to 3 km (depending on wavelength used).
- For very short range (-50 m), there is problem due to requirement to generate very short pulse.
- It is not suitable for robot guidance and control.

Laser Sensors (Chapter 4)

- High resolution is possible.
- Use of 10.6 μm wavelength ensures low attenuation, except due to dense fog (fog attenuation data inconsistent).
- It is possible for vehicle-mounted and along-the-guideway application.
- Robot guidance and control is possible but requires more research and development effort.

Digital Signal Processing (Chapter 5)

- Various types of image characteristics have been considered:
  - (a) reflectivity image (2D X vs Y),
  - (b) PPI impage - echo range vs scanning angle,
  - (c) range image (2D X vs Y or θ vs ϕ) representing echo time (or distances),
  - (d) wide beam image (2D impage representing intensity as a function of time and scanning angle).
- The processing required to analyze the input images to produce output giving location and some size information of an obstacle is relatively simple.
- Hardware for this type of processing appears to be commercially available.

Conclusion and Recommendation (Chapter 6)

- One system cannot fulfill all the requirements.
- For vehicle-mounted system, either millimetre wave radar or laser radar sensors is recommended (details are given in Chapter 6).
- Along-the-guideway, above-track mounting of laser radar system appears most suitable. The same approach is usable for level crossing application (see Chapter 6).
- Robot guidance and control application would require more precise definition of the requirement.
- A three-phase development program based on laser radar principle is proposed.
    (a) Phase I - Design of the System
    (b) Phase II - Building of the System
    (c) Phase III - Field Testing of the System

1/ INTRODUCTION

1.1/ Background of the Study

This report on Active Vision Sensor Technology is submitted to the Transportation Technology Office of the Ontario Ministry of Transportation and Communications in fulfillment of the requirements of the Ministry's request dated August 17, 1984 (Project #31670). Mr. J. Tsai of the Transportation Technology Office, is the program manager for the study.

The object of the study is to review the state-of-the-art in active vision sensor technology, and in particular, microwave radar sensors, laser radar sensors and sonar (ultrasonic) sensors. The two main application areas anticipated are object identification on the guideway, and guidance and control of stationary or moveable robots for inspection or cleaning. Active vision sensors are defined as those providing their own source of illumination.

The balance of Chapter 1 is devoted to a general discussion of the problem and of active vision sensing techniques.

Following this, Chapter 2 discusses sonar and ultrasonic detection techniques, Chapter 3 covers radar, including millimeter wave radar, Chapter 4 discusses laser systems, and Chapter 5 is devoted to digital signal processing and image processing. Finally, in Chapter 6, conclusions and recommendations from the study are given.

1.2/ Discussion of the Requirement

1.2.1/ Detection Situation Envisaged

A number of applications scenarios can be visualized. We can divide these, first, into two main areas, guideway surveillance for object detection and identification, and robot guidance and control.

In guideway surveillance, there are four possible arrangements, which lead to differing requirements.

(a) the active sensor is mounted on the vehicle, looking forward along the track.

(b) sensors are mounted along the guideway, at the sides, or above, each covering a section of track. An «alarm» condition is signalled to an approaching train by radio or other means, or alternately signalled to a central train dispatcher as in current railroad CTC systems.

(c) sensors cover level crossings. This situation is very similar to (b), and might be satisfied by the same solution, but the required ranges are smaller, the nature of the objects potentially different, the probability of obstacles is greater and the required number of installation is smaller. Thus, a somewhat more complex and expensive system might be justified.

(d) sensors cover the guideway in the station area. Again the situation is similar to (b) and (c), but the different emphasis in the requirements might justify a different approach. Also the environmental conditions are different.

A guideway surveillance sensor mounted on the vehicle, would require to have a reasonably long range, say 3 km, as high a resolution as possible in both range (distance) and in the two transverse angular dimensions (vertical and horizontal). It should cover the full guideway width at a distance of, say, 300 metres, which will probably mean that it will cover ten times the guideway width at 3 km. See Figure 1-1.

A system of sensors distributed along the guideway would use a number of detections systems, each having a wider angular coverage and a shorter range. However, the shorter the range of each system, the more systems are required to cover a given length of guideway, so the range cannot be made too short. On the other hand, the potential advantages of such a distributed system lie in the possibilities of achieving greater resolution of objects far ahead on the guideway than is possible with a vehicle mounted system. This implies that the individual systems not have too great a range. A spacing of 300 metres might be suggested, with the understanding that the actual optimum will depend on the technology used and on the cost per system, installed and maintained. The use of a distributed system implies communications to the vehicle controls, either on the vehicle, or at a remote control point.

The requirements for level crossing sensors are similar, except that they can be shorter in range without implying a larger total number, and that economics would permit a more sophisticated detection and processing system. A system with

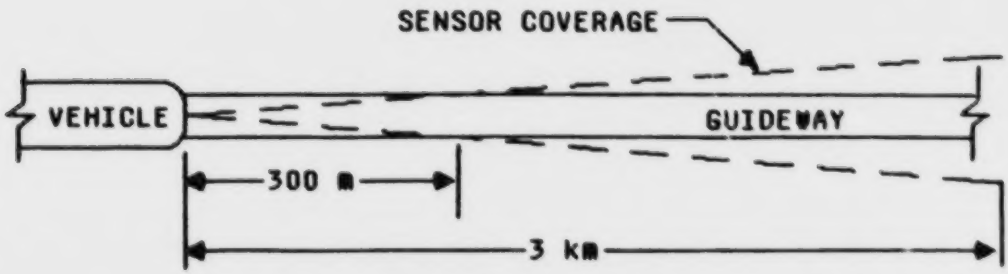

Figure 1.1/ Sensor Mounted on Front of Vehicle

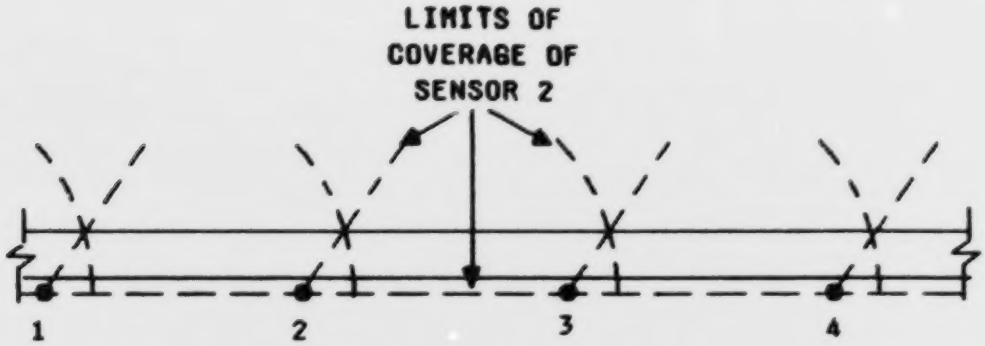

Figure 1.2/ Sensor System Distributed Along Guideway

Figure 1.3/ Level Crossing Surveillance

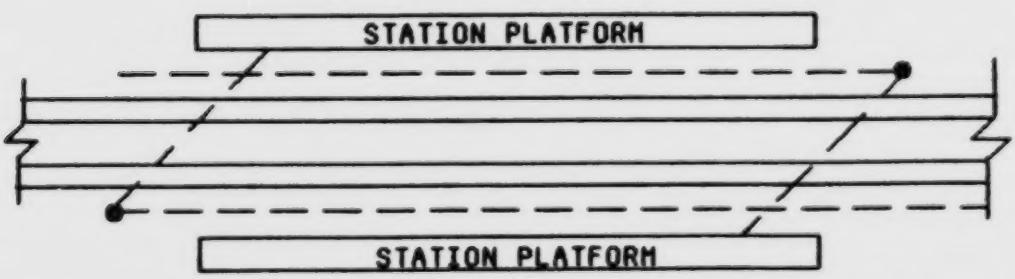

Figure 1.4/ In-Station Surveillance

sufficient resolution to identify people and cars would be desirable. The shorter range requirement might well lead to use of a different technology. See Figure 1-3.

The in-station guideway surveillance presents a problem somewhat similar to the level crossing requirement, except that targets of interest are likely to be smaller (e.g. people) and the area to be covered somewhat longer. Because of the smaller number of stations, installation of redundant systems might be considered.

The requirements for robot vision for inspection and cleaning present a quite different requirement. The most demanding part of the robot control task is the very short distance requirement, distances less than 1 metre. It will be seen in the following that this essentially eliminates pulsed radar, because of the shortness of the time intervals involved. (FM-CW radar is still a possibility). Many of the requirements for robot terminal guidance might be achieved through the use of small beacons (low power radio or light transmitters) or of retroreflectors located on the object to be cleaned or inspected. For inspection, a camera type imaging system, probably with a self contained illumination source to avoid shadowing might be the simplest approach. Several compact CCD imaging systems for inspection are available.

1.2.2/ Types of Vision Sensor

The most common type of vision sensor is the television camera. We have excluded this from the present study, as it is not fundamentally an <u>active</u> vision sensor, although it is

possible to add an illumination source to the camera system, and even to make the system insensitive to ambient light by means of a filter which will pass only the light from the illumination source.

The active sensors on which this study has concentrated are ultrasonic sensors, microwave (including millimeter wave) radar sensors, and laser sensors, primarily laser range finding sensors (laser radar).

The discussion of ultrasonic sensors discusses developments in underwater sound (sonar) and in medical uses of ultrasonics, in order to show the state-of-the-art, particularly in the signal processing, but with the realization that our applications will require the use of ultrasonic sensors in air. The more limited work which has been done in this latter field is reviewed and related to our requirements.

The field of microwave radar is reviewed to relate radar sensors to the needs of transportation situations. The discussion concentrates on millimeter waves and the advantages, disadvantages and limitations of millimeter wave radar from our standpoint.

The discussion of laser sensors deals mostly with laser radar or range finding sensors, based on the same echo delay principle used in conventional radar and in sonar. Imaging systems, triangulation using lasers, and holography are briefly discussed.

1.2.3/ Types of Image

Since this study deals with «imaging devices», we should define what we mean by an imaging device. A television camera

produces an image which is similar to that which our eye sees, i.e. it produces a display (picture) in which the horizontal and vertical position of a point (x,y) represents the horizontal and vertical angles (θ,ϕ) to the point and the brightness represents the brightness of the scene at (θ,ϕ). We could call this an optical image, but it is not the only type of image.

Radar type devices measure range, and angular position, usually in only one plane (horizontal or vertical). They can produce images, in the sense that they are more or less recognisable plane representations of a physical situation, but they differ considerably from optical type images. We will call these plan type images. This is because they present the situation, not as would be seen by an observer looking from the position of the radar, but as would be seen by an observer suspended above the area scanned. The coordinates of the image represent distance to the point from the radar, and angular location of the point seen from the radar, and the brightness indicates the radar scattering cross section of the object, or part of an object, located at the point. The radar scattering cross section of an object may differ considerably from its visual impact, so the radar plan type image may differ considerably from an optical aerial image in appearance.

Even optical type images may differ considerably, and if the imaging detector uses wavelengths other than the visible, the reflectivity, and hence the intensity variation in the image, may be much different.

Another difference between many optical type images, and the image seen by the eye is that most optical type images are not binocular, and therefore lack an important element of range information. It would not be difficult to obtain binocular images, using two cameras, but this does not fall under the scope of the present study. It is possible, though, to obtain range information within the framework of an active optical imaging system by making time of flight (echo delay) measurements.

1.2.4/ Types of Data Output

The actual output of most sensors is a voltage or current which varies with time. This applies to television cameras, as well as to sonar, radar and laser sensors. This time varying signal is interpreted in terms of the known characteristics of the sensing system to give the useful data outputs.

The output of a camera system produces three items of information for each resolution cell within the image: horizontal angle, vertical angle and intensity. The output of a radar type sensor gives one or two angular coordinates, depending on whether the sensor scans only in one angular dimension or two, and range and amplitude (intensity) of any return observed at those angular coördinates. Some radar sensors also make possible a direct measurement of range rate; the rate at which range is changing.

1.2.5/ Data Processing

The raw data outputs of the vision sensing system can be used to drive a cathode ray tube (CRT) display system if the decisions are to be made, or monitored by a human being.

In order to implement automatic decision making, and in some systems, in order to refine the data to extract improved information from it, complex computations using a digital computer may be required. This topic is discussed in the section on digital signal processing and, also, in connection with specific sensors in appropriate sections of the text.

2/ SONAR

2.1/ Introduction

Sound is virtually the only form of energy that can propagate effectively (with tolerable attenuation) underwater, where electromagnetic waves are rapidly attenuated. The term «SONAR» (acronym for Sound navigation and ranging) has been defined (1) as «the method or equipment for determining by underwater sound, the presence, location or nature of objects in the sea». The reasons for the numerous applications (2,3,) of underwater sound (which dates back to the turn of the century) are several favourable acoustic properties of water (or any liquid) compared to air (or gases). Thus:

(a) The specific acoustic impedance of water is several order of magnitudes higher than air. This allows high conversion efficiency of launching the sound energy into the liquid from the transducer.

(b) The speed of sound in water (1500 ms/sec) is 4.5 times faster than in air. This favours measurement of larger range from the echo times which may be too long in air for some applications with fast moving targets.

(c) The attenuation of sound (4) in water is also tolerable (Fig. 2.1) for the detection of targets at large distance (several kilometers). In contrast, the attenuation in air is rather strong causing further severe limitations on the range ($\sim$ 100m). This point will be further examined in Section 2.4.

In this Chapter we will discuss the «SONAR» principle as applied to underwater sound applications mainly to point out the state-of-the-art development of the technique with the increasing introduction of digital signal processing technology. It is to be noted many of the design concepts have exact parallel in the modern radar design.

In Section 2.4 we will explore the possibility of acoustic radar for object detection and ranging in air. In Section 2.5 some of the recent developments in ultrasonic imaging will be summarized.

2.2/ SONAR Principle

An active SONAR, as illustrated(5) in Fig. 2.2, involves transmission of an acoustic signal which, when reflected from a target provides the SONAR receiver with a basis for detection and estimation. The problem addressed in active SONAR is to detect a target and estimate its range or radial velocity in time. From the range and the radial velocity estimates one can in principle determine the target location. Thus let us assume a signal $S(t)$, $0 \leq t \leq T$ is transmitted. If the target is at a nominal range Ro and moving with a radial velocity v the received echo is

$$e(t) = a(R)\ S\left((1-\alpha)\ t-\tau\right) \qquad \ldots\ldots \qquad (2.1)$$

where $a(R)$ = attenuation factor due to propagation loss

$\alpha = 2\ v/C$ $\qquad$ C = Speed of sound

$R = Ro + vt$

$\tau = 2\ Ro/C$

Thus the echo is delayed by τ, which is the propagation time to the target and back. Also depending on the sign of v, the echo is a

time compressed or expanded version of the transmitted pulse. If the bandwidth of the transmitted signal is sufficiently narrow with respect to the center frequency of the transmitted signal (ωo), the effect of time compression and expansion can be seen as a frequency shift (Doppler Shift)

ω_D given by

$$\omega_D = \frac{2v}{C} \omega_o \qquad \ldots\ldots \quad (2.2)$$

As in radar, the approximate estimates of SONAR system performance can be made using the so called SONAR equations, which can be refined through subsequent detail statistical analyses.

In its simplest form (2) the active SONAR equation can be written as

$$SNRAV = SL - 2TL + TS - (NL - DI) \qquad \ldots\ldots \quad (2.3)$$

where

SNRAV = signal to noise ratio(dB) available to the receiver

SL = source level of the sound (in dB relative to one micropascal

TL = one way propagation loss in dB

TS = target strength in dB, a parameter related to target reflectivity

NL = noise level at the receiver in dB relative to 1 μpa

DI = directivity index of the receiver array in dB

Under certain conditions, the noise at the SONAR receiver is dominated by reverberation, in which case the noise (NL-DI) is replaced by the reverberation level RL observed at the output of the receiver array. Once this estimate of the available SNR is made it is compared with the

SNR required to reach performance goal. This is not quite straightforward as the SNR required depend on a number factor such as time spreading and frequency spreading of the signal as it propagates through the complicated ocean medium.

2.3/ SONAR Signal Processing Functions

In this section we introduce some of the important concepts of signal processing which are used in the design of modern SONAR systems. These concepts, in general, are also used extensively in the design of modern radar signal processing. Fig. 2.3 shows the block diagram (5) of a generic active SONAR system with its major functional elements. The signal or waveform generator consists of an oscillator which generates a baseband signal and some form of a modulator. The signal is then delayed in time by various amounts (called inverse beamforming) to generate a set of signals which is applied via a set of transmit/receive switch to an array of «projectors» (transducers). The array of projectors serves to «focus» the sound energy in a pre-specified direction. The receiver subsystem processes the received waveforms from each hydrophone element into a suitable form for operator interpretation. In preparation for digital processing, the signals are first filtered in a signal conditioner, amplified or attenuated using an automatic gain control (AGC) or time-varying gain (TVG) in the dynamic range control, and finally digitized by an A/D converter. The digitized outputs from the sensors are combined to form a set of «beams» in a beam-former. Various types of digital beam forms which are a combination of hardware/software units have been discussed by several authors (6,7,8,). These data are then bandshifted and filtered for further processing to obtain

appropriate detection and estimation statistics. The final output is a display of these statistics from which the operator can make decisions and in some cases computer-generated decisions.

2.3.1/ Waveform Design

Waveform design (in Sonar and Radar) concerns the choice of an appropriate signal that can provide

(a) sufficient energy for detecting targets and estimating their parameters;

(b) sufficient resolution of targets;

(c) sufficient rejection of unwanted echo.

In short, the type and quality of information received by a sonar (or radar) depend in part on the waveform it transmits.

A very important technique (9) called pulse compression employs a pulse that has a linearly increasing (or decreasing) frequency. When the echo is passed through the receiver (matched) filter the energy is compressed into a short time interval, thereby providing much better time resolution. Thus, using such a waveform one can provide simultaneously the large energy of the long uncompressed pulse, and the high time resolution of the shorter compressed pulse. The receiver filter used in Sonars (and radars) is called matched filter. This filter maximizes the signal-to-noise ratio when the noise is additive white Gaussian and provides the most detectibility of the targets. In the early fifties Woodward (10) described a unified theory of radar resolution that combined the notion of pulsed compression and matched filters into a single useful function called the «ambiguity function».

This function describes the resolution properties, the ambiguities, the measurement precision, and the clutter-rejection properties of radar signals and has become the principal mathematical tool in the design and study of radar and sonar signals.

2.3.2/ Ambiguity Function

A detailed discussion of the ambiguity function is beyond the scope of this review. Readers are referred to several authoritative treatments of the subject as in references 9, 10, 11, 12. In this section we try to bring out the essential features of the concept and its implications in the radar and sonar design. The ambiguity function describes the complex envelope of the signal at the output of the radar (or sonar) receiver matched filter as a function of target range and radial velocity. The function is defined by the following integral (9).

$$X(\tau,\phi) = \int_{-\infty}^{\infty} u(t)\, u^*(t+\tau)\, e^{-j2\pi\phi t} dt \quad \ldots\ldots \quad (2.4)$$

where

τ = difference between the time the signal actually arrives and the time to which the filter is matched.

ϕ = difference between received Doppler frequency and Doppler frequency to which the filter is matched.

These parameters (i.e. τ and ϕ) are related to actual range R_r and the matched range R_m, and the actual radial velocity V_r and the matched radial velocity V_m by

$$\tau = \frac{2\,(R_r - R_m)}{C} \quad \ldots\ldots \quad (2.5)$$

and

$$\phi = \frac{2\,(Vr - Vm)}{C}\ fo \qquad \ldots\ldots \quad (2.6)$$

The ambiguity function has its peak value at the origin, indicating that the largest signal output occurs when a target has the range and velocity to which the filter is matched. One can obviously interpret the ambiguity function either as a correlation function or as a weighting function.

Two fundamental properties of the ambiguity function concern its maximum value and the volume under $\left|X\ (\tau,\phi)\right|^2$.

The maximum value of the ambiguity function occurs at the origin

$$\left|X\ (\tau,\phi)\right| \leq X\ (0,0) = 2E \qquad \ldots\ldots \quad (2.7)$$

Where E is the signal energy, this is the so called «thumbtack» function. (9)

The second property of the ambiguity function is that the volume under $\left|X\ (\tau,\phi)\right|^2$ is a constant and independant of the shape of the waveform.

Thus

$$\left|X\ (\tau,\phi)\right|^2 = \iint_{-\alpha}^{\alpha} \left|X\ (\tau,\phi)\right|^2 d\alpha, d\phi = \left|X(0,0)\right|^2 = (2E)^2 \quad \ldots \quad (2.8)$$

Thus, if one attempts to narrow the mainlobe of the ambiguity function, the sidelobes will increase or other peaks may appear. Thus waveform design can never eliminate the volume under $\left|X(\tau,\phi)\right|^2$; all proper waveform designs can do is to try to move the inevitable volume to regions in the $\tau\ \phi$ plane that are relatively free of clutter and other interfering targets.

Figure 2.4 shows some classes of ambiguity functions(9). Many

waveforms exist to approximate the «thumbtack» ambiguity functions(9). Two of the common types are those with non-monotonic frequency modulation and those with pseudo-random pulse coding - either position, phase or frequency.

In practice, however, the matched filter condition which is optimum for white noise may not be satisfied. For example, in active sonar with reverberation dominated noise the use of a matched filter is not optimum since the power spectral density of reverberation is not flat. It is, however, common practice to use a matched filter and estimate a degradation index (13).

2.3.3/ Time Sampling

Since modern sonar signal processors are digital computers, it is necessary to sample the received waveforms at discrete times. For simplicity, the sampling is done at equal time intervals. It is well known (14), that in order to preserve the character of the analogue waveforms one must sample at a faster rate for rapidly varying waveforms than for slowly varying ones. The sampling rate which preserves the information content of an analog signal X(t) is termed the Nyquist rate (14,15,). If X(t) is a deterministic signal band limited to $B/2\pi$ Hz, then one must sample at rate B/π samples per second, the Nyquist rate. There are several techniques of sampling discussed in literatures (5,16,). Some common techniques are:

(a) Quadratic sampling

(b) Delay sampling

(c) Analytic signal sampling.

Readers are referred to the literatures for details of the techniques. One important point to note is that Nyquist rate assumes «ideal» filters. In general any realizable filters have a finite roll-off. In practice, therefore, one must sample at a rate higher than the Nyquist rate. As an example, for low pass sampling, the sampling rate is usually about 2.5 times the highest frequency.

2.3.4/ Spatial Sampling and Beamforming

Another important function to be performed in the sonar system is beamforming (5). The sensor array in the sonar receiver samples the acoustic pressure field (i.e. spatial sampling) while the beamformer combines the sensor outputs in an appropriate fashion to yield enhanced detection and estimation. In order to understand the function of beamforming one can look into the frequency wave number spectrum $P(\omega,\vec{k})$ of the acoustic field. For instance, targets usually radiate energy which is narrow band in nature. Also, since the target is spatially compact this energy arrives from a given direction. Thus the frequency-wavenumber spectrum of the acoustic field due to such a target might be

$$P(\omega,\vec{k}) = C_1 \; e^{-a(\omega-\omega_o)^2 \; -b\left|\vec{k}-\vec{k}_o\right|^2}$$

which is sharply peaked at $\omega = \omega_o$ and $\vec{k} = \vec{k}_o$

However, the $P(\omega,\vec{k})$ for the noise field which is uncorrelated in time and space would be

$$P_n(\omega,\vec{k}) = C_2$$

Thus, by estimating the spectrum one can determine the presence of a target as well as determine its frequency and direction. The estimation of the wavenumber portion of the spectrum is known as beamforming in sonar terminology. To understand the concept of beamforming let us assume a linear array. Assume one wants to detect the presence of a plane wave signal $s(t-\vec{r}.\vec{n}/c)$ which is propagating with known direction $\vec{n} = \vec{k}_o/|\vec{k}_o|$ and is measured at $\vec{r}$ in a background of white noise. Since the noise is spatially white, it is uncorrelated from sensor to sensor (this is a good approximation for half-wavelength spaced sensors and isotropic noise). A reasonable way of processing the array data is to combine the sensor outputs after delaying the element outputs to account for the propagation delay of the wavefront. This process,, in addition to improving the signal-to-noise ratio also provides spatial discrimination. This is because any other plane wave propagating at a different direction than that assumed by the beamformer will not combine coherently and thus will be attenuated. One can then talk about the «beam pattern» of the array like the gain of an antenna system in radar. Ideally, one would like to have a beam pattern with narrow main lobe and low-level side lobes for maximum noise rejection. Techniques of achieving these have been discussed in literatures (17,18 in detail.

2.3.5/ Band Shifting

Band shifting is employed in active and passive sonars to reduce the complexity of the hardware and software required for subsequent processing. This is usually implemented digitally at the output of the beamformer. In active sonars, the received signal is contained in a very narrow band, typically about 1 KHz, centered at some high frequency typically about 15 KHz. To avoid having to sample the received signal at the Nyquist rate of 30 KHz, it is more convenient to demodulate the process to baseband and then employ sampling of the complex envelope at 1 KHz.

2.3.6/ Filtering

Filters are used extensively in sonar systems, accounting for large portion of the processing load. In Fig. 2.3 it is seen that analog filters are used in the signal conditioners where as digital filters are employed (19,20,), in conjunction with band shifting and also implicitly in the detection/estimation statistics processor. Digital filters used in sonar signal processors perform two major functions:

(a) Filtering of the waveform to modify the frequency content;

(b) Smoothing of waveforms to reduce the effect of noise.

In the first category some typical applications are the separation of frequency bands for passive sonar processing, generation of the complex envelope process, the reduction of the sampling rate following a time delay beamformer.

In the second category some applications are matched filters for detection, background normalizers for setting

detection threshold and smoother/trackers for parameter estimation. The two generic type of digital filters are FIR (Finite Impulse Response) and infinite impulse response (IIR) filters. The input/output relationship for the two filters are:

$$Yn = \sum_{k=o}^{L-1} h_k X_{n-k} \qquad \text{(FIR Filter)} \quad \ldots\ldots \quad (2.9)$$

$$Yn = \sum_{k=1}^{N} a_k y_{n-k} + \sum_{k=0}^{M-1} b_k x_{n-k}$$

(IIR Filter) . . . . (2.10)

The detail design and implementation of these filters are available in references (21,22,).

2.3.7/ Decision Processing

The ultimate goal of sonar is to extract the relevant features of the acoustic space-time field and to put them in a format which the sonar operator can interpret in terms of the sources which generate the field. After the initial data reduction processes, the final stage is the decision processing (5,23,) which involves the following functions:

(a) Detection

(b) Classification

(c) Estimation

(d) Normalization

(e) Display processing

The mathematical basis of decision processing is provided by the theories of hypothesis testing and estimation (see for example Ref. 23, 24, 25).

These theories share a common element in that each provides a rule for interpreting observed data in terms of hypothesized signal and noise models. For hypotheses testing there is the decision rule which when applied to an observed data vector ($\vec{R}$), specifies one of several hypotheses about the PDF (Probability Density Function) of the data. In its simplest form, the detection (for example) is a binary hypotheses testing problem where the «null» hypothesis (Ho) is «noise only» data and the alternative hypothesis (H1) is «Signal plus noise» data. Classification on the other hand, is typically a multiple hypotheses testing problem where, for example, H1 = submarine target signal plus noise, H2 = freighter signal plus noise, H3 = surface ship signal plus noise, etc. In a similar fashion, estimation theory which applies to both parameter estimation and tracking gives the estimation rule to compute the unknown parameters of the signal component (point estimation) or gives probabilistic bounds on their values (interval estimation).

Most sonar detection and estimation structures can be implemented through combinations of filtering, Fourier transformation and straightforward equation evaluation. Tracking and display processing functions generally require implementation at low data rates. These algorithms are typically performed in general purpose computers which are also used to control the system. More recently, these tasks have been allocated to micro-processors in the distributed processing architectures used to implement modern sonar.

In the above discussions we indicate the rapid introduction of digital signal processing in sonar system. The impact of digital technology on sonar will be even greater in the coming years. The impact will be felt not only through the form of the hardware itself but through the complicated processing techniques which become feasible with digital implementation.

2.4/ Acoustic Radar Sounding in Air (An Assessment)

As mentioned earlier, the generation of high intensity sound fields in air is severely limited because of the relatively low acoustic impedance (42 acoustic ohm per square centimeter) of the medium (26). The acoustic power generated in air by a vibrating piston is given by (26)

$$P_A = \frac{42\ \omega^2\ d^2\ A \times 10^{-7}}{2} \quad \text{watts} \quad \ldots\ldots \quad (2.11)$$

where $\omega = 2\pi f$; f = frequency in C/S

d = peak displacement of the piston in cm

A = area of the piston in cm^2.

Fig. 2.5 shows the plot between the peak displacement of a vibrating surface and the acoustic power radiated from the surface at various frequencies. It can be seen that for a peak displacement of 0.001" only a few watts/sq. inch can be generated at low ultrasonic frequencies. There is, therefore, a practical limit of increasing the acoustic power radiated and coupled in air due to maximum tolerable amplitude of vibration of the ultrasonic transducers without reaching fatigue failure. Furthermore, one encounters harmonic distortion when the peak acoustic pressure is an appreciable fraction of the atmospheric pressure. Another limiting factor is the attenuation of ultrasound in air.

Fig. 2.6 shows the attenuation in dB per foot of sound in air as a function of frequency (26). These factors severely limits the range of the acoustic radar to, at the most, 100 m depending of course on the frequency employed.

However, one application of acoustic radar has been found (27,28,) to be at least partially successful. This concerns the probing of the lower atmosphere. The reason behind this is that the effect of fluctuations of temperature, wind and humidity on the acoustic refractive index of air (the real part of the complex refractive index) are 1000 times stronger than in the case of electromagnetic waves. Since the scattered power is proportional to the square of the refractive index fluctuations, the scatter of acoustic waves from atmosphere may be expected to be roughly 1 million times stronger than for radio waves. The optimum frequency for an acoustic radar for atmospheric sounding has to be compromised between the increase in directivity and improved resolution against the undesired attenuation experienced as the frequency is increased. The optimum frequency is a strong function of the range over which the radar has to work, being lower for larger ranges because of attenuation. Calculations show expected 26 dB SNR for a range of 150m at 5 kHz. At ten times range (1.5 km) the atmospheric absorption will be about 100 dB (10 dB for 150m) making a lower frequency imperative. For a range of 1.5 km one would require 100 watt 100 ms pulses at 1 kHz radiated and received by a $10m^2$ acoustic antenna.

It appears, however, that the possibility of using an acoustic radar for range finding over 100 m with good directivity is not practical.

A successful ranging system based on ultrasonics but suitable only for ranges 0.9 ft. to 35 ft. with an accuracy of $\pm \frac{1}{2}$ " is the range finder in the Polaroid ultrasonic range finding Camera (SX-70). The latest (30) Texas Instruments sonar-ranging module, the SN28827, is actually an updated and higher-functioning version of the original SX-70 module. Figs. 2.7, 2.8, 2.9 show the specification, parts and the beam pattern of the ultrasonic transducer operating at 50 kHz. The sonar-ranging module is shown schematically in Figure 2.10. Recently Jarvis (29) in analysing the requirements of three-dimensional scene analysis in support of vision driven robotic manipulation came to the conclusion that implementation of direct range finding capabilities can greatly reduce the computational burden for reliable determination of the placement and spatial extent of objects in the scene. Unfortunately, however, his assessment of the SX-70 ultrasonic range finder for such application is discouraging mainly because the large solid angle of the main energy lobe ($\sim$30°) which he found unsuitable for achieving rangepics of spatial resolution better than about 4 x 4. His evaluation of the laser range finders have been discussed in Chapter 4.

2.5/ Ultrasonic Imaging in Medicine

In this section we briefly describe some of the most recent application in medical diagnostics using ultrasound. The ultrasonic waves used in medical diagnosis (30) have frequencies in the megahertz range. Most medical diagnostic applications of ultrasound depend on the fact that pulses are partially reflected at boundaries between media that differ in their characteristic impedance. At the boundaries between kidney tissue and fat tissue only 0.5% of the incident energy is reflected.

Such echoes, although small, are easily detectable by sensitive receivers. As in radar and sonar, the ultrasonic diagnostic system is based on pulse echo measurements. These pulse echo information obtained from human body can be displayed on a CRT in several different ways. One way (called A-scan) is the usual range display where the horizontal axis represents the time required for the echo to return, corresponding to the distance between the reflecting structure and the probe, the vertical axis corresponds to the strength of the echo. In another form of display (called B-scan), each echo is represented by a spot of light on the screen (brightness modulated display). The position of the spot represents the position of the echo producing interface while the brightness represents the strength of the echo. The B-scan also forms the basis of an imaging system that is particularly important in medical diagnosis: a system that forms pictorial images of 2-D cross-sections through the body. In order to form such an image the ultrasonic probe is mounted on a mechanical scanner that moves in two dimensions. The scanner then provides the data base not only on the strength of the echo and the distance of the source from the probe, but also on the position of the probe and the direction of the beam. At each position of the probe, the echoes are returned along the path of the beam. The position and the brightness echo are stored in a scan converter and displayed. In a typical digital scan converter the image information is split up into a regular 2-D matrix of small picture elements (512 x 512). The position of each of the picture elements corresponds to the location of a «word» in a RAM. The brightness of each element corresponds to the value of the word. The above 2-D scanner takes between 3 to 15 seconds to build up an image of one full cross-section through the body. This type of

system is not suitable for scanning moving structures such as heart or rapidly searching a large volume for a particular feature. In such situations, a real time scanner is needed. The 2-D scanner outlined above can be adapted for real time scanning by moving the probe back and forth across the patient at such a rate that the sequence of images it generates, freezes the action of the moving feature. Another way of implementing real time scanning is to use an array of transducers that are operated one after the other in rapid sequence in order to scan the organ repeatedly in 2-D. The resolution of the system can be improved, in principle, using a large number of transducers in the array and processing the signals by computers.

The principle of Doppler shift of ultrasound is also widely used in medical diagnostics of moving organs such as the fetal-heart detector.

The techniques mentioned above are being widely used in medical diagnostics as is evident in looking through various medical literatures on diagnostics (32,33,34,).

The most recent interest in the use of ultrasound for diagnostics has been in the area of computerized tomography (35,36,), in which a cross-sectional image of an object can be accurately reconstructed if its projections or line integrals are known at all angles. Greenleaf (36) in a recent article discusses the mathematical basis of computerized tomography with ultrasound and the problems with implementation.

2.6/ Conclusion

In this chapter we discussed the state-of-the-art development of sonar and ultrasound imaging. We discussed the underwater sonar development to indicate the rapid introduction of signal processing theories and digital techniques in sonar system. Many of the concepts of signal processing are similar to Modern Radar Techniques. As for its possible application as a rangefinder in atmosphere its range is severely limited and do not appear attractive for the application of obstacle detection and identification through ranging. Jarvis's (29) idea for its use in robotic vision application will require development of large array transducers.

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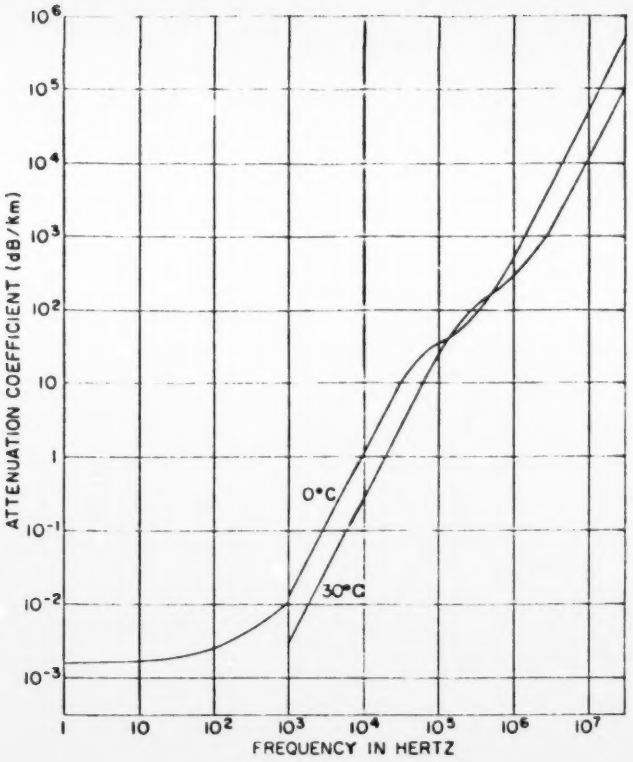


Attenuation coefficient calculated by (1) and (3) with $S = 35‰$. The effect of hydrostatic pressure is neglected.

Figure 2.1/ Calculated Attenuation Coefficient

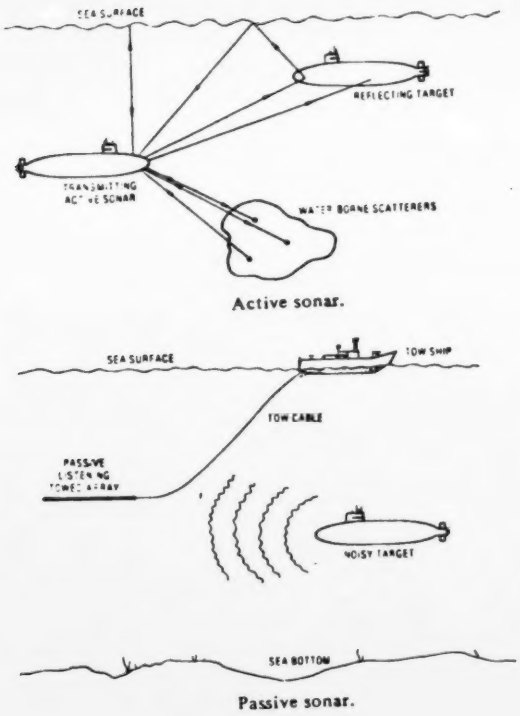
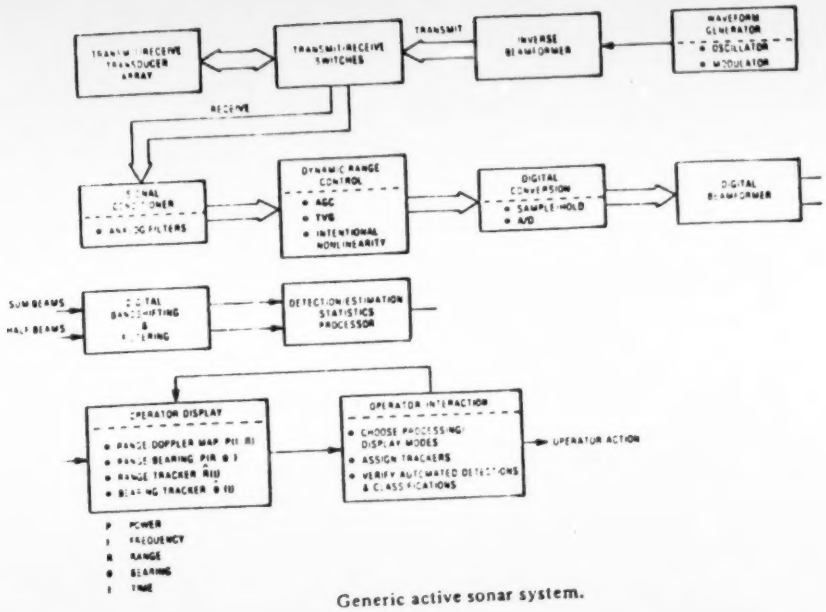
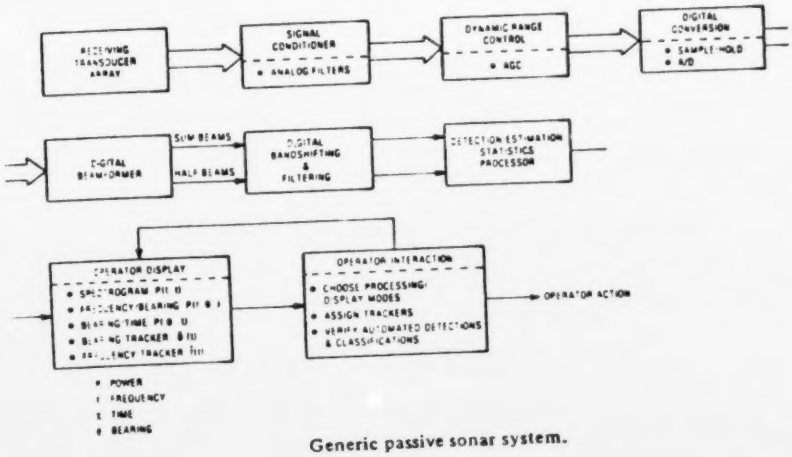


Figure 2.2/ Sonar Principle

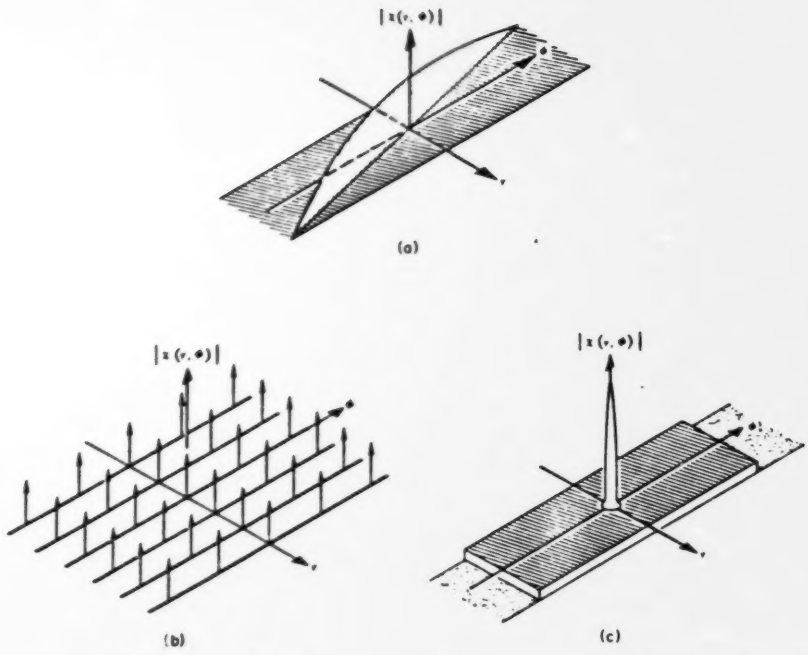


Generic active sonar system.



Generic passive sonar system.

Figure 2.3/ Sonar System



Classes of ambiguity functions: (a) knife edge (ridge); (b) bed of spikes; (c) thumbtack.

Figure 2.4/ Classes of Ambiguity Functions

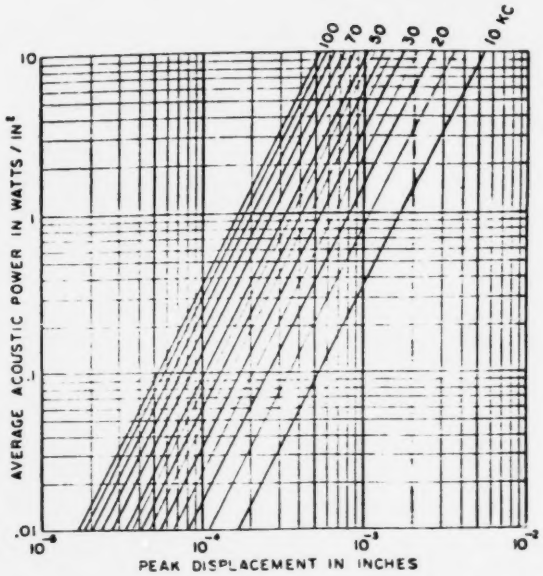
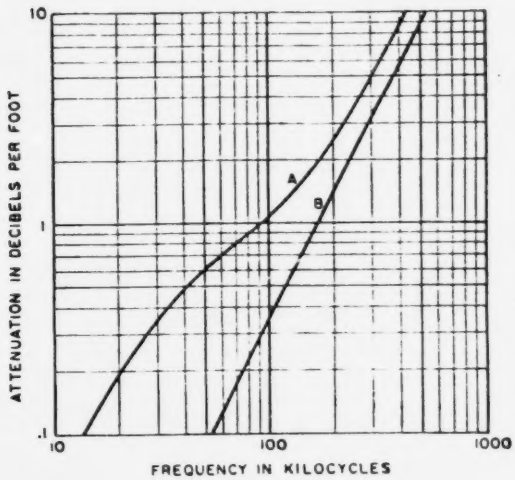


Figure 2.5/ Relationship Between Peak Displacement of a Vibrating Surface and the Acoustic Power Generated at Various Frequencies



Absorption of sound in air as a function of frequency. Curve *A* is the average of experimental data for average atmospheric conditions 75°F and 37 percent relative humidity. Curve *B* is the theoretical attenuation for dry air from classical theory.

Figure 2.6/ Absorption of Sound in Air as Function of Frequency

Specifications	
Minimum Transmitting Sensitivity at 50 kHz 300 V AC peak to peak, 150 V DC bias (dB re 20 μPa at 1 meter)	110 dB
Minimum Receiving Sensitivity at 50 kHz 150 V DC bias (dB re 1 V/Pa)	– 42 dB
Suggested DC Bias Voltage	150 V
Suggested AC Driving Voltage (peak)	150 V
Maximum Combined Voltage	400 V
Capacitance at 1 kHz (typical) 150 V DC bias	400-500 pF
Operating Conditions	
Temperature	32°-140° F
Relative Humidity	5%-95%
Standard Finish	
Foil	Gold
Housing	Flat Black

Figure 2.7/ Specifications for the Polaroid Electrostatic Transducer

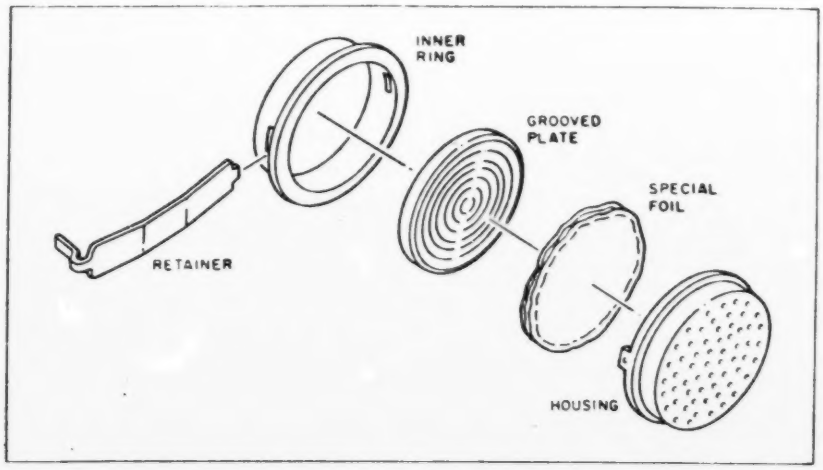


Figure 2.8/ Parts of the Polaroid Electrostatic Transducer

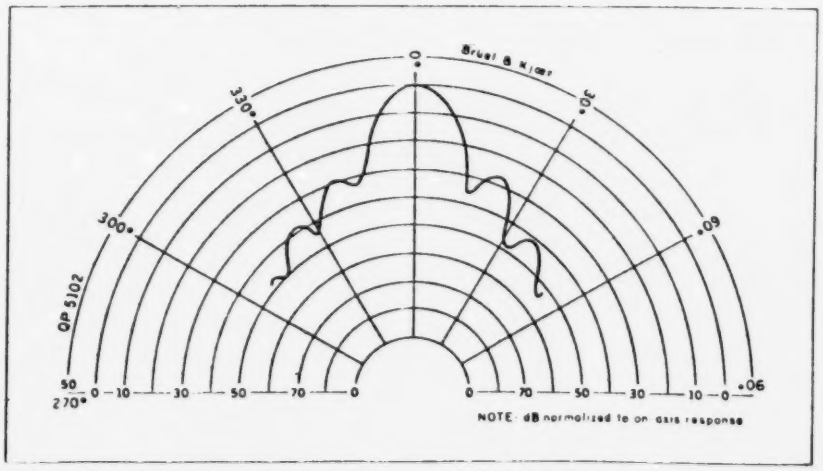


Figure 2.9/ The Transducers Beam Pattern at 50 kHz

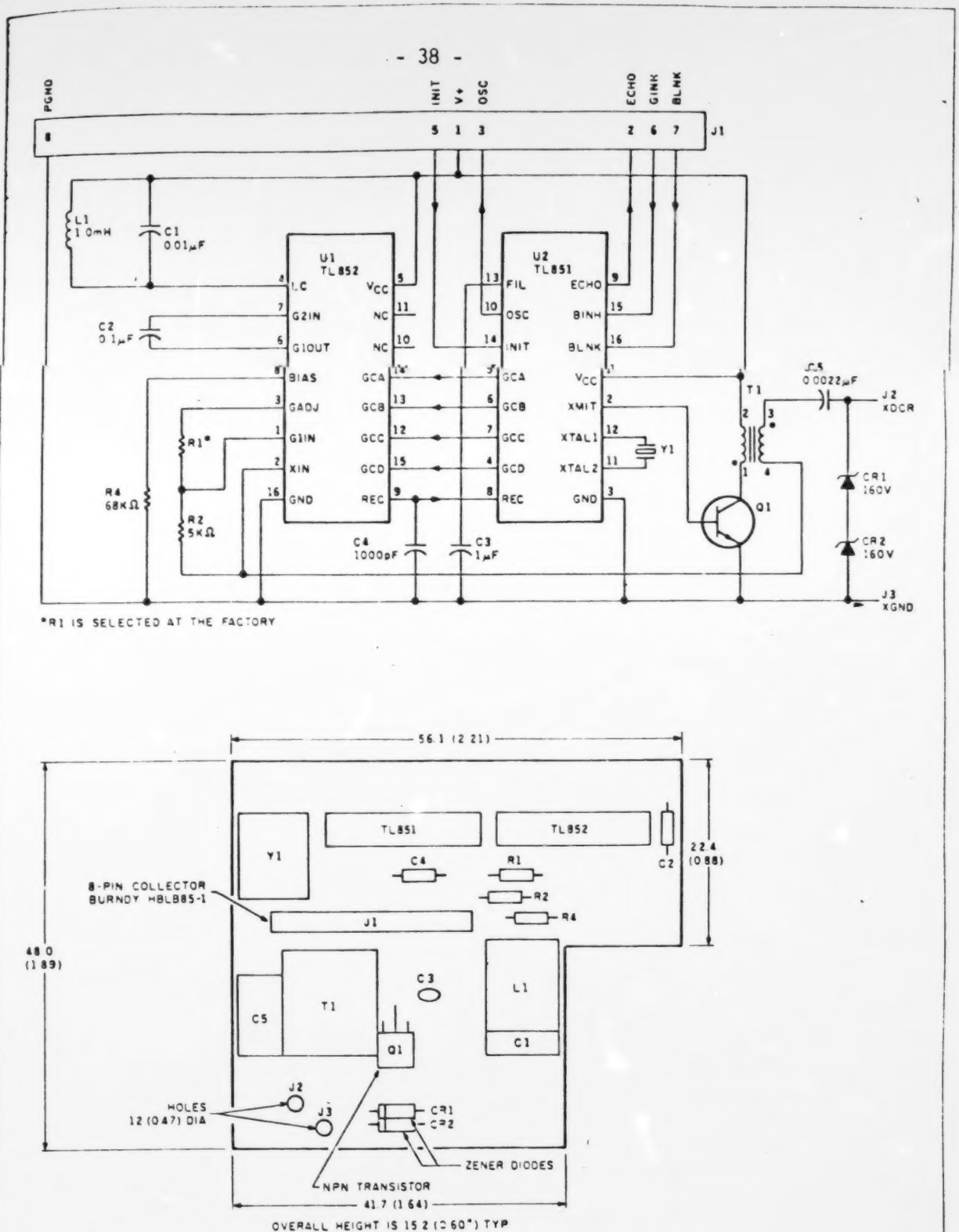


Figure 2.10/ The Schematic and Layout of the Texas Instruments Sonar-Ranging Module

3/ MICROWAVE RADAR

3.1/ Introduction

The term "Radar" originated as an acronymn for 'Radio Detection and Ranging'. It denotes systems that determine the presence, location and possibly the shape of objects by means of radio waves. The angular position of the objects, or 'target', is determined by the orientation of the radar beam as controlled by the antenna system; the range to the object is measured by the time delay between the transmission and the return echo of a radio pulse. The velocity of propagation of the pulse is close to the velocity of light (3×10^8 m/sec), so that time delay is in fact proportional to the range.

The origins of radar go back to the 1920's, when it was observed that radio signals fluctuated when airplanes passed nearby. Radar underwent rapid development prior to and during World War II. Frequency ranges were in the MHz band, with demonstration of a 12 MHz pulse radar system in 1935 and sea trials of a 200 MHz system in 1939. By the end of the war systems operating at 9GHz (9000MHz) were in use and experimental systems at 24GHz had been developed. There ensued a diversification of the basic radar into various types of pulse, CW, pulse-Doppler and MTI radars, with a variety of pulse compression and signal processing and display techniques. Today, operational radars employ sophisticated computer data processing systems which allow simultaneous tracking of several targets and precision tracking in Cartesian co-ordinates.

3.2/ Basic Radar System

A basic radar system is shown in Figure 3-1. The transmitter produces an electromagnetic signal which is sent out

in the direction of the target, usually in a narrow beam. If the beam strikes the target, some reflected energy (echo) is returned to the sending location where it is amplified and detected by a receiver. An antenna is used to produce the narrow transmitting or receiving beam. In principle, separate antennas could be used for transmitting and receiving, and sometimes are, but in most cases a single antenna is used for both transmitting and receiving, using a duplexer to direct energy from the transmitter to the antenna, and to direct received echoes from the antenna to the receiver. A variety of detection, processing and display, or other output utilization schemes have been used. In most radar systems range is measured by determining the time between transmission of a signal and the reception of the reflected signal or echo. The main components of a radar system are discussed briefly in the following.

The transmitter consists of a high power amplifier tube, together with its associated power supplies, cooling and shielding systems (1). A typical radar tube, the magnetron, can deliver as much as 200 KW peak power at 10 GHz. There are two basic tube types, Crossed-Field Tubes (M type) and Linear-beam tubes (O type). Tubes which fall under these two categories are listed in Figures 3-2 and 3-3. In both types of tube, an electron beam is caused to oscillate in sympathy with nearby RF fields, and so give up part of its kinetic energy to the RF field energy. Crossed-field devices make use of the fact that electrons travel at right angles to perpendicularly oriented electric and magnetic fields. Re-entrant M-type tubes are circular in cross-section, with a magnetic field parallel to the

axis of the tube and a radial electric field. Electrons describe circular paths around the axis of the cylinder (Figure 3-4). Nonre-entrant M-type tubes are constructed in a linear format, so that electrons pass by the RF field interaction only once. Linear-beam O-type tubes are similar but the electron beam is accelerated by an electric field parallel to the length of the tube; focussing is by a magnetic field also parallel to the tube axis.

There are over 1000 different types of microwave tubes, each designed for particular characteristics of bandwidth, power-handling capability, ease of manufacture and size. Tubes are designated resonant and non-resonant depending on the design of the RF path which brings the RF signal periodically close to the electron beam. There are forward and backward wave devices, depending on the direction of the flow of RF energy wih respect to the electron beam direction. Some devices are designed to be amplifiers, others are designed to be oscillators. The exact choice of device for a given application depends on the careful selection of up to a dozen different parameters. Travelling-Wave Tubes (TWT's), for example, are broad-band devices while Klystrons are designed more for high power over a narrow band of frequencies.

More recently, a variety of solid state sources have become available for use in systems transmitting moderate power, a few watts to hundreds of watts average power, depending on frequency.

3.2.1/ Duplexer

In a pulsed radar system, the RF energy from the transmitter is generally passed to the antenna through a duplexer. This is a transmit/receive switch which couples the transmitted energy to the antenna and the received energy to the receiver while protecting the receiver from the high-power transmitter output. Duplexers are usually either of a gas-discharge type for high power or a ferrite circulator for low to medium power (2).

3.2.2/ Antenna

The function of the antenna is to collimate the transmitted signals, i.e. to send them out in a narrow beam, and to collect echo signals from the target illuminated by this narrow beam. In the case of a CW radar or of a bistatic radar (one with receiver and transmitter in different locations) separate antennas are employed for the transmit and receive functions. Most radars use antennas producing narrow beams. Three basic types of narrow beam antennas exist, reflectors, lenses and phased arrays. Perhaps the commonest type is the reflector antenna. The parabolic dish antenna produces a pencil-beam which can be used in tracking a target; the parabolic cylinder reflector produces a fan beam often used in a search radar operating in the azimuth co-ordinate. In both types of reflector the microwave beam can be directed at the reflector from a feed horn placed at the focus of the reflector, or from a small Cassegrain reflector element placed near the focus which redirects rays from a feed horn at the centre of the main dish (Figure 3-5). Alternatively, the reflector system can be

designed to place the feed horn off-axis from the main dish (3). Reflector antennas are based on optical principles like reflecting telescopes, and are analogous in design. The beam from a reflector antenna can be moved (scanned) by rotating the whole antenna, or by moving the feed only. Moving the feed can produce only a limited angle of scan. Many complex and ingenious schemes have been developed for scanning the beam from a reflector antenna.

A lens antenna consists of dielectric material placed in the path of the microwave beam (Figure 3-6). The lens is shaped in such a way that the desired beam pattern is produced by bending the rays from the feed horn. That is, lens antennas are also based on optical principles. Lenses and reflector antennas are, in general, interchangeable, and can be used for producing a pencil beam, a fan beam or any other shapes of radiation beam.

A major obstacle to very rapid scanning of a narrow antenna beam to allow it to search a volume of space is the inertia of the antenna or of the moving feed. Array antennas (4) consist of a great number of similar fixed radiating elements,such as slots or dipoles, each element being individually controlled in amplitude and phase. Using such an array, the shape and direction beam can be rapidly and accurately controlled in a highly predictable manner, allowing rapid search of a volume of space, or the simultaneous tracking of a number of targets.

3.2.3/ Receiver

The receiver amplifies the echoes of the radar transmission and filters them so as to provide the maximum

discrimination between desired echoes and undesired interference. By mixing the input signal with local oscillator signals, the echo signal is downshifted in a series of stages to the IF frequency appropriate for the detector. The detector provides identification of a particular feature of the signal that is of interest. This can be, for instance,

- a filter bank to monitor the frequency
- a sampling or scanning spectrum analyzer
- an amplitude peak detector
- an rms amplitude detector
- an averaging amplitude detector
- a phase synchronous or switching detector, to measure echo phase or very small shifts in frequency

3.2.4/ Display or Other Signal Utilization

The display system converts raw radar output to usable information. It can consist of analogue circuits, such as filters and control loops, and/or digital circuits that interface with a dedicated processor unit. Displays are of many types, ranging from the basic A-scan (a plot of intensity versus range) to plan-position (map-like) displays and various types of Doppler displays. On the other hand, in guidance or tracking systems the processor output may be used for feedback to a positioning or control system rather than for display.

3.2.5/ Timing and Control

The timing and control unit determines the proper synchronization and timing of signals throughout the radar system. The basic PRF (pulse repetition frequency), gating functions for range information, antenna sweep control and display waveforms are provided by this unit.

3.3/ Radar Principles

3.3.1/ General

In this section, we will discuss the principles of operation of various types of radar with specific reference to applications in active vision sensing for use in transportation systems. Because of the scope of the subject, and the great mass of theoretical and practical work done over the past forty to fifty years, the treatment will not be exhaustive, but will attempt to highlight those factors which are of interest or utility in our application.

Summarizing our interests quickly, we will bear in mind a number of possible situations -

(1) A radar sensor mounted on a vehicle, surveying the guideway in front of the vehicle to detect obstacles.

(2) Radar sensors mounted along the guideway, maintaining surveillance on a fixed section of guideway. Special cases of this would be surveillance at level crossings or in stations.

(3) The use of low power radar sensors at short ranges for guidance and control of automated maintenance and cleaning devices (maintenance/cleaning robots)

(4) The use of low power radar sensors in automated inspection.

In the latter two cases, we might consider the possibility of creating a situation in which the targets are effectively co-operating targets by using simple electronic transponding devices, attached temporarily or permanently to the object, or possible to the environment, to aid in automatic location or orientation of the robot device.

3.3.2/ Antenna Principles

As indicated in 3.2 the antenna is used in radar to send out electromagnetic energy (radio waves) toward the target area and to receive reflected electromagnetic energy (echoes) from any targets present in the volume illuminated by the transmitted beam. Since, in most cases, the direction of the beam is used to determine one or both of the angular co-ordinates of the target, an antenna beam which is narrow in one direction (fan beam) or in both (pencil beam) is desired for most applications in radar.

This is unlike the situation with AM radio, for instance, in which we want an antenna which receives more or less uniformly from all directions, i.e. which is nearly isotropic. Sometimes, however, as with TV reception in fringe areas, we may want an antenna with a more directive beam pointing in the direction of the desired station. Such an antenna is said to have a higher gain or a greater directivity. Gain is usually stated in dB with respect to a hypothetical isotropic receiver (or radiator):

$$\text{Gain in dB} = 10 \log_{10} \frac{\text{Power Received by the Antenna in Questi}}{\text{Power Received by an Isotropic Antenna}}$$

or for the case of a transmitting antenna (radiator):

$$\text{Gain in dB} = 10 \log_{10} = \frac{\text{Power Transmitted in a Given Direction by the Antenna}}{\text{Power Transmitted in the Given Direction by an Isotropic Antenna}}$$

where the total power transmitted is the same for the test antenna and the isotropic antenna. The gain of an antenna is the same for transmitting as it is for receiving.

Since we compare our antenna with an isotropic antenna radiating the same total power, it follows that if we radiate more power in one direction we must radiate less in other directions. We can think of the gain, defined as above, as a function of the angular co-ordinates θ and ϕ. See Figure 3-7. What we have, above, called the gain of the antenna is the maximum value of this gain function. The shape of this function, plotted against θ and ϕ is called the pattern of the antenna. Although the pattern is actually a three dimensional figure, we usually think in terms of two patterns, an azimuth pattern and an elevation pattern.

The pattern of an antenna never consists simply of a narrow main beam with no energy at all in other direction. There is always some energy transmitted in other directions than the main beam, and if there were targets in those directions echoes would be received from them. These unwanted parts of the pattern are called sidelobes. They are unwanted because the radar system always makes the assumption that any signal received is due to something in the main beam, so any response due to a sidelobe is a false target. Sidelobe levels are measured in dB with respect to the main beam. See Figure 3-8.

If a sidelobe is a dB below the main lobe, the response from a given target will be 2s dB below the response from the same target in the main lobe, since the lower level of the side lobe will affect both the transmitted signal and the received echo. However, this advantage can be offset if the sidelobe looks at a target with much larger cross section than one in the main beam at the same range.

Generally, the higher the directivity of an antenna for a given wavelength the larger its size. The Yagi antennas used for enhanced TV reception in fringe areas are larger than the rabbit ears or loops used for local reception in the same frequency bands. Dishes used for satellite reception are even larger, even though the frequency is much higher.

There is no exact relationship between the maximum gain of an antenna and its physical size. Instead we can relate the maximum gain to what is called the effective area of the antenna, its effective size. This is generally smaller than the physical dimensions, sometimes much smaller. The relationship between maximum gain and effective area is

$$G = \frac{4\pi A}{\lambda^2}$$

where λ is the wavelength and A the effective area. The concept of effective area can be extended to an effective area function. $A(\theta, \phi)$ analogour to the gain function, the effective area mentioned above, A, being the maximum value of this function, corresponding to G the maximum value of the gain function $G(\theta, \phi)$.

The behaviour of many types of high gain antenna can be visualized most easily in terms of optical principles. (On the other hand, low gain antennas, in which we have little interest for our present purposes, are best visualized in terms of circuit and transmission line concepts.) The term microwave optics is often used. The most common high gain antenna for microwave use, for instance, is the parabolic reflector, which is, in principle, identical with the parabolic mirrors used in searchlights or in telescopes. Energy from the radar transmitter can be fed to the parabolic reflector through a feed horn at the focus of the parabola. See Figure 3-5. It is often more convenient to feed the energy through the centre of the parabolic reflector from the back, and to use a small hyperbolic reflector to redirect the energy onto the reflector surface. Such a system is called a Cassegrain feed and is derived from the Cassegrain telescope long used in optical telescopes.

The difference between microwave optics and visible light optics is, in fact, only a difference in wavelength, but because of the factor of 10^4 - 10^6 between microwave wavelenths and visible light wavelengths, diffraction plays a much larger role in microwave reflector behaviour than in optical reflectors. A microwave reflector can only be thought of as producing a parallel beam for a relatively short distance, a few times its lateral dimension, while a visible light reflector may produce a beam which is essentially parallel for thousands of times its diameter. Nevertheless, at large enough distances, both must ultimately be treated in terms of angular beamwidth. (The crossover distance is about $2D^2/\lambda$ where D is the diameter of the reflector.)

The optical analogy in antenna design carries further to the use of lenses as antennas. Any low loss (i.e. non absorbing) dielectric material can be used to make a microwave lens, and if fed by a horn at its focus, it will produce a directive beam from the opposite side of the lens. See Figure 3-6. The requirement for a lens, as for a reflector or other type of directional antenna, is that it produces a constant phase across a plane surface in front of the antenna. That is, the optical path length from the feed point, to all points on this plane surface must be the same. Since the optical path length through a dielectric is equal to the index of refraction, μ, times the actual length, a dielectric lens must be thicker at the centre than than at the edges to produce a directive beam (since μ is always greater than 1 for a dielectric). See Figure 3-9.

At microwave frequencies, the phase changes produced by dielectrics can be simulated by other structures, such as arrays of balls, rods, or metal plates, and lenses can be made from these structures. Metal plate lenses can have an effective index of refraction less than 1, so some metal plate lenses are thicker at the edges than in the center.

Lenses offer more flexibility in design, since there are two contours to vary as well as the dielectric constant, so it is possible to design lenses to produce good focus for beams which are at an angle to the axis of the lens, as well as for those on axis. This means they are somewhat better suited to steering the beam by moving the feed point only. (See later discussion of beam scanning.) Nevertheless, lens antennas are not nearly as widely used as reflector antennas.

Another type of large area antenna in which the optical analogy is less obvious is the array antenna. In an array antenna, energy is brought individually to a very large number of points on the surface of the antenna, usually a rectangular array of points in a plane. If the energy is fed to all of these points at the same frequency, with the same phase, a directional beam is produced, at right angles to the surface of the array. Further, the beam can be steered to other angles by introducing a linear phase taper across the surface of the array. For this reason such antennas are often called phased arrays. See Figure 3-10

In discussing directional antennas, especially for radar applications, it is often simpler to think in terms of beamwidth than gain. A narrow beamwidth means a high gain but the exact relationship between beamwidth and gain is not simple. It is derived by integrating the radiated power over the whole three dimensional gain function or pattern of the antenna.

To define the shape of the beam, even approximately, we must give two beamwidths in orthogonal planes, generally the horizontal (azimuthal) and vertical (elevation) beamwidths. The beamwidth is related to the effective dimension of the antenna in the corresponding plane measured in wavelengths. An antenna with a large horizontal dimension in wavelengths produces a narrow horizontal beamwidth. Antenna beamwidths are usually measured at the point where the radiated power (or received signal) is 3dB down from the peak value. See Figure 3-8 . (Sometimes the half voltage points, -6dB, are used, and occasionally the 1/e voltage points.)

The relationship between half power beamwidth and antenna dimension, in the same plane, is

$$\theta_b = k \frac{d}{\lambda}$$

where d is the dimension of the antenna in the same units used for measuring λ. k is a constant the maximum value of which is of the order of 1/50 if θ_b is measured in degrees, but which may vary considerably from one antenna design to another.

Beam width is important in radar applications since it determines the maximum angular resolution in the image of the area scanned.

All current radar imaging surveillance systems (See section 3.6 for a discussion of what we mean by imaging in the radar content) require that a narrow beam be scanned over the area to be coverd at a rate which depends on the application. For long range surveillance the rate may be slow enough that the whole antenna system can be moved (e.g. rotated in the horizontal plane) to cause the beam to scan over the area of interest. In fact, the beam motion must not be too rapid, since the echo from a target due to a transmitted signal must return before the beam has moved past the target position, and for long range radars, it is usually required that sufficient time be allowed for many echoes to return during one beamwidth to increase the system sensitivity. On the other hand, where the range is shorter and the reaction to information gathered must be rapid, as would be the case in most transportation applications,

the rate of scan must be high. This means that systems which scan by motion of low inertia parts, such as feed systems, or which require no actual physical motions for scanning, are preferable, although it is also true that at very high frequencies (e.g. millimeter or submillimeter wavelengths) the whole antenna size becomes small enough that moderately rapid scanning is not out of the question.

The subject of scanning antennas is too extensive for a detailed treatment here. The beam of a parabolic antenna can be steered, or scanned, by moving the feed only, leaving the reflector fixed, but this can be done for only a very few beamwidths before the shape of the beam degrades too seriously to be useable. Many complex and often ingenious devices have been invented to achieve rapid scanning by motion of low inertia elements. The reader is referred to Chapter 15 of reference 5, which is a good reference on other antenna topics also.

Another approach to rapid scanning of antenna has been developed extensively since the publication of reference 3.5. This is the use of the phased array. We have already discussed this briefly as a means of forming a high gain antenna beam. Because it is formed from individually phased elements it is adapted to beam steering or scanning by controlling the phase of the individual elements, which can be done either with small mechanical motions, or in the case of completely electrical control, with no mechanical motion at all. See Figure 3-11. It is even possible to set up the phase shifting network so that, with only a limited number of values of phase shift applied by the different phase shifters in the network, any required beam

position can be obtained. This is ideal for digital control of beam position. With such a system the beam moves in small jumps rather than smoothly, but as long as the different beam positions overlap sufficiently this is no problem. Using this technique, the antenna no longer poses a limit to the rapidity with which the beam can be scanned.

Before leaving the subject of antennas, a word concerning the means by which the radio frequency is fed to and from the antenna is in order. At the lower frequencies used in television flat two conductor twin-line is usually used. At higher frequencies or for longer distance there is too much pick-up of interference, or radiation of power for open twin-line to be used, so coaxial cable with one conductor in the centre and one surrounding it, with dielectric spacing, is used. At still higher frequencies, those used in radar, the losses in coaxial cable become too high, so waveguide of rectangular, or sometimes other, shape is used. This acts like a pipe for electromagnetic energy. A horn is a flared section placed at the end of a waveguide to direct the energy onto a reflector or lens. See Figure 3-12.

Sometimes, special forms of printed circuit board wiring called strip-line or sandwich-line are used for microwave circuits or phased array antennas.

3.3.3/ The Radar Equation and Cross Section

The radar equation relates quantitatively a number of characteristics of a radar system with the "size" of the smallest target it can detect at a given distance. Here "size" is not physical size, but the effective size for the radar, a quantity

known as radar cross section. This usually depends on a number of factors in addition to physical size, such as shape and material e.g. refractive index and/or conductivity of the material, and for most shapes it will depend strongly on the orientation of the object to the radar beam.

The radar equation actually gives the received power, P_R, expected from a target of radar cross section, σ, at a range, R, using a radar transmitting power, P_T, at a wavelength, λ, using an antenna with transmitting gain, G_T, and a receiving gain, G_R. (normally $G_T = G_R$). The equation is

$$P_R = \frac{P_T \, G_T \, G_R \lambda^2 \sigma}{(4\pi)^3 \, R^4}$$

Setting P_R = the minimum detectable signal would give the minimum value of σ detectable at a given range with the other radar parameters given.

The radar equation is the straightforward result of calculating the energy radiated in the direction of the peak of the antenna beam which falls on an area σ at distance R and assuming it is re-radiated uniformly in all directions (isotropically). The radar receives the amount of power which falls on the effective area of the antenna, which as we have said previously is related to the gain by

$$G_R = \frac{4\pi A_R}{\lambda^2}$$

i.e. $$A_R = \frac{G_R \lambda^2}{4\pi}$$

The radar cross section of a target may be looked on as the cross section (projected area) of a smooth reflecting sphere which would return to the radar the same amount of energy as the target actually does. The radar cross section of a target depends very strongly on the orientation of the target. A target may give a strong echo when oriented in one way, and practically no echo when oriented in another. For instance, a perfect cube, made of smooth reflecting material (e.g. polished metal), and with sides a number of wavelengths across, would have a very high radar cross section (very much larger than the actual area of one side) when any of the six sides was facing directly toward the radar (i.e. normal to the radar beam) but a very low cross section when oriented in any other direction. See Figure 3-13. With more complex or irregularly shaped objects the variation of cross section willl be less extreme, and there will generally be a very large number of lobes to the radar cross section pattern as the object, not the radar, is rotated.

While this variation of response from the same target, depending on its exact orientation, may be a problem in identifying a target by its radar response, there are other cases in which we may take advantage of the dependence of cross section on shape or other target characteristics.

Often it is useful to be able to identify the location of some fixed or moving object which may be too small to give a sufficiently strong and reliable radar return to be easily identifiable. It would be useful to be able to greatly enhance the echo from this fixed or moving object so that it would stand out clearly. This can be done with a passive, broadband device

called a retroreflector. The retroreflector has a radar cross section which is very much larger than its actual projected area, but unlike the flat (outside) face of a cube, it exhibits this behaviour over a wide range of angles. The simplest form of retroreflector for microwaves is obtained by cutting off the corner of a large cube and orienting its inside faces generally toward the radar. See Figure 3-14. This corner cube retroreflector retains a large cross section over about one eighth of the total solid angle. Eight such corner cubes stacked with their apexes together will give almost complete, although not constant, coverage at all angles. There are also other types of retroreflector, such as that based on the Luneberg lens, which offer some advantage at the cost of slightly greater complexity. It should be noted that the beaded screens, and other textured screens, used in projecting slides or home movies, the reflective tape used on car bumpers, and the reflective paint used on highway signs are crude forms of optical retroreflectors. High quality corner cube retroreflectors are also available for use at visible light frequencies.

Another special case of anomalous cross section behaviour that should be mentioned is that of chaff. The common form of chaff is thin metallized fibre glass hairs which are cut to a half wave length of the expected radar frequency. At this length they are resonant and each fibre, despite its fineness, has a large cross section. They are so fine that, when released in the air, they settle slowly. A cloud of these fibres, thrown out of an aircraft to confuse the tracking radar on an enemy

missile, may have a total cross section many times that of the aircraft itself, despite the fact that the whole cloud may weigh only a few ounces.

Chaff is not likely to be encountered in transportation situations, barring mischief, and it is not easy to obtain, but it does illustrate the fact that, even to radar, an "object " need not be of sufficient solidity to represent a hazard, in order to present a substantial radar echo.

3.3.4/ Target Range

The term "radar" is an acronym for the descriptive name "radio detection and ranging", where "ranging" means measuring the distance to a target. Almost all so called radar systems are still based on the measurement of range by using the velocity of propagation of electromagnetic (radio) waves, although the term radar has been used in connection with some systems which perform detection only without ranging (e.g. bistatic radar fences). The common technique is to send out short pulses of electromagnetic energy, and to measure the time interval between transmission of the pulse and reception of echoes. Since electromagnetic radiation travels at 3×10^8 metres/sec in free space. and at essentially the same speed in air, a time interval of 0.66×10^{-8} seconds is observed for each metre of distance to the object. (Note that the radiation has to travel twice the distance to the object i.e. to and from the object.) Another way of stating this is that there is 150 metres of target distance for each microsecond of delay in receiving the echo.

Radar systems usually send out a series of equally spaced pulses, so that a series of echoes are received from each target. It is obviously much simpler if the next pulse in a sequence is not sent out until the echo from the most distant target we can detect is received. If this is not done the picture can be confused by what are called "second time around" returns. See Figure 3-15. If we wish to look at targets up to 3000 metres from the radar the highest allowable pulse repetition frequency from this standpoint would be 50,000 pulses per second but it would be better to use pulse repetition frequencies much lower (say 10,000 pps) to avoid interfering echoes from large targets farther away than 3000 metres, which would appear as false targets apparently at (actual distance - 3000 metres) or at (actual distance - n x 3000 metres).

The transmission of pulses and measurement of echo delay time is not the only means of determining range in radar systems. Another approach is to use a continuous transmission (called CW for continuous wave) which is continuously varied in such a way that when a reflected signal is received from a target, after travelling to the target and back, the travel time can be determined by comparing it with the signal then being transmitted. The simplest way of doing this is by transmitting a signal the frequency of which changes linearly with time. Then the frequency difference between the received signal and the signal being transmitted is a direct measure of the travel time and, thus, of the distance to the target. See Figure 3-16. This is the basis for most radar altimeters, and is also used for other situations in which the distance to a single relatively large target must be measured or controlled. This technique (FM

radar) can also be used with multiple targets but the processing is more complex. A less common technique is to vary the amplitude, phase or frequency of the transmission in a random manner (noise or pseudo-noise modulation) and to use correlation techniques in comparing the returned signal with the transmitted signal to determine the travel time for the returned signal.

It is, perhaps, worth noting that the same distance measuring techniques used in radar are used in other situations, such as the location of faults in transmission lines and cables. In this application the echo delay technique is known as time domain reflectometry.

3.3.5/ Electromagnetic Waves Polarization and Propagation

Electromagnetic waves, which include both radio (or radar) waves and light, consist of the propagation of electric and magnetic fields through space or other media. In our case we are concerned with propagation through air, which is very little different from free space, from the standpoint of electromagnetic waves. They are called electromagnetic waves because the energy propagated is continuously and periodically being transferred from electric fields to magnetic fields and back. Thus, the electric field varies continuously, in a sinusoidal manner, from a maximum in one direction to a maximum in the opposite direction. See Figure 3-17. In free space, air, or most unbounded media, the electric field is normal to the direction of propagation. Electromagnetic waves are characterised by frequency, wavelength, polarization and velocity.

The frequency is the number of times per second that the electric (or magnetic) field reverses itself as the wave travels through any medium. The frequency of an electromagnetic wave does not change, except when some nonlinear operation is performed on it. (This normally occurs only in circuits or in some crystalline materials under special conditions.) Waves at a number of frequencies may travel together, though, so a beam of energy may contain many different frequencies.

Wave length depends on the medium through which the waves are travelling, being essentially the same in air and in free space, but being shorter in ordinary dielectric and dielectric filled cables, and longer in waveguides. For some purposes, however, the effective path length travelled by energy depends on the number of wavelengths, so if the wavelength is shorter than the free space value, the effective path length is longer than the physical distance travelled.

The velocity of propagation of electromagnetic waves in free space is the same for all frequencies or wavelengths. It is approximately 3×10^8 metres/second, and is essentially the same in air. The velocity of propagation can never exceed this value, but in dielectrics and dielectric filled cables it may be much less. It is also less in waveguides, but the situation is complicated here by the existence of another "velocity", the so called "phase velocity". This merely means that from some standpoints (e.g. the wavelength or distance between maxima in the electric field) the wave acts as if it had a larger velocity, but the actual velocity of propagation of energy (here called "group velocity") is always less than 3×10^8 metres per second (called "c"). Expressed in the form of equations, the relations are:

$$v_p = \lambda_g/\lambda \quad , \quad v_g = \lambda/\lambda_g$$

and $v_p v_g = c^2$

where v_p = phase velocity

v_g = group velocity

λ_g = wave length in the wave guide

λ = wave length in free space

c = velocity of propagation in free space = 3×10^8 m/s

These equations assume the waveguide is filled with air. They would be modified if the waveguide contained a dielectric.

The polarization of an electromagnetic wave is the direction of the electric field, which, as pointed out before is always at right angles (transverse) to the direction of propagation. (Here we are considering only free space type propagation, i.e. propagation in unbounded media, not in cables or waveguides). If we assume the direction of propagation to be horizontal, the polarization can be horizontal (but normal to the direction of propagation) or vertical or anywhere in between. The intermediate cases can be treated as consisting of horizontal and vertical components having the same phase (i.e. reaching their points of zero value at the same time). For instance, two waves of equal amplitude and with the same phase travelling in the same direction, one having vertical polarization and one having horizontal polarization are equal to one wave of $\sqrt{2}$ times the amplitude with 45° polarization, i.e. half way between horizontal and vertical. Polarizations of this type are called "linear". See Figure 3-18.

Another case of interest is the combination of two waves of equal amplitude and travelling in the same direction, one vertically polarized and the other horizontally polarized, but with a 90° phase difference, rather than being in phase. That is, one wave has its points of zero electric field half way between the points at which the other reaches zero electric field. The combined electric field vector never becomes zero, but continually changes its angle, rotating about the direction of propagation in either a clockwise or counterclockwise direction. This is known as "circular" polarization, and has some important applications in radar. Its use is claimed to reduce interference due to rain.

The propagation of electromagnetic waves in the atmosphere is affected by a number of considerations. Among these are:

(1) the geometric spreading of the beam energy over a larger area as we go farther from the transmitter. This results in the $1/R^2$ power variation for one way transmission or the $1/R^4$ variation of returned power in the radar case.

(2) atmospheric attenuation. This is due mostly to absorption of electromagnetic energy by water vapour in the air and in some frequency ranges by oxygen. For ranges of even a few kilometres attenuation due to absorption can be significant compared to the geometric attenuation toward the short wavelength end of the millimeter wave band. Below 10 GHz it is negligible at all ranges.

(3) precipitation attenuation. This can be quite serious, but, the short ranges with which we are dealing reduce the problem. Here also the effects are more serious in the millimeter wave band than at lower frequencies. Dry snow is much

less of a problem than rain. See later discussion under "Atmospheric Effects" (Sec. 3.7).

(4) fog attenuation. This is generally less serious than rain in the radar frequency range, even at the higher millimeter wave fequencies.

(5) ducting. This is an effect due to guiding of waves by atmospheric inversions, and has caused some anomalous results on long range radars (returns from unexpectedly long ranges producing false targets). Because of the short ranges we are dealing with it is unlikely to cause any problems in our applications.

3.3.6/ Signal Detection and Signal To Noise Ratio

The output of a radar system, following each pulse which is transmitted, is a series of small return pulses each being the result of the reflection of part of the energy from the transmitted pulse by an object (target) which is located within the beam of the radar antenna. These small reflected pulses are called echoes.

There are three main items of interest concerning any target. These are (1) the fact that it is there (2) where it is exactly, that is, what is its range, and what are its angular co-ordinates as seen from the location of the radar, and (3) what it is. The last point is often the most difficult to decide, and we will leave it for later discussion.

The distances from the radar transmitter/receiver to the target can be determined by the time delay between the transmission of the pulse and the reception of the echo. The angular co-ordinates of the target are determined by the angular position of the beam at the time the pulse is transmitted and the echo received.

In principle, the existence of a target is shown by the presence of an echo. If there is no target there should be no echo. However, two factors make this simple conclusion invalid. The first is that there may be other objects, which are not real targets from our standpoint, that is, which produce real echoes but which are not the sort of objects we are interested in. We call this clutter. The second is that the electrical circuits, unavoidably, produce a small, randomly fluctuating output signal, even when there are no echoes received. We call this noise.

Clutter echoes may be produced by the ground itself, by buildings or other structures beside the guideway and partly illuminated by the beam, by rain, by birds or by wind-borne inanimate material. Clutter is usually strongest at short ranges because of the $1/R^4$ term in the radar equation, and may saturate the receiver at short ranges. One solution to this is sensitivity time control, which makes the receiver sensitivity low immediately after the pulse is transmitted and allows it to increase slowly during a short interval following the pulse transmission. The exact interval would depend on the application, but in our case would be, at the most, a very few microseconds.

Some amount of noise is unavoidable, so the task of the receiver designer is to try to keep it as close as possible to the minimum value prescribed by the laws of physics. This theoretical minimum value is KTB watts where $K = 1.38 \times 10^{23}$ joules/degree Kelvin (Boltzmann's constant), T is the temperature in degrees Kelvin, and B is the effective bandwidth in Hz. A measure of how good the receiver design is in minimizing

additional noise is the "noise figure", F. If the noise figure is F the effective input noise, competing with the received echo power as given by the radar equation, is FKTB watts. F is often given in logarithmic form (decibels) as FdB where

$$FdB = 10\log_{10}F.$$

The best possible value of F will depend on the frequency, it being more difficult to get low noise figures at the higher microwave frequencies. Practical noise figures lie in the 3 to 20 dB range.

Noise is a random phenomenon so the above figures are average power taken over a period of time. Instantaneous noise voltage, as seen at the output of the receiver detection circuits may have any value. The value corresponding to the average power is the r.m.s. (root mean square) noise voltage. Values of instantaneous noise voltage become less and less probable (i.e. less and less frequent in occurrence) as they become larger compared to the r.m.s. voltage. See Figure 3-19. A value of noise of three times the r.m.s. level will occur on the average only once in every 370 pulse lengths (assuming the receiver is designed to match the transmitter pulse length.) For a value of 4 times the r.m.s. level the average frequency is one in 16000 pulse periods.

This means that if we examine the output of the radar receiver, rather than seeing a signal which is zero except when there is an echo from a target, we see a signal which differs from zero most of the time, with occasional higher values which may or may not be true echoes. If one of these higher values is

many times the r.m.s. level we can be relatively sure it is a true echo, but if it is only, say, 10dB above the r.m.s. level there is a 0.2% chance that a signal of this size might be produced by noise alone. This may sound small, but it means that there is a probability of almost 50% of having at least one occurrence of a signal of this level or higher in 340 samples equal to the pulse length, which might correspond to the observation period following the transmission of a pulse. Thus, in order to avoid frequent false "echoes", it is necessary to establish a threshold below which apparent returns are ignored. This may lead to failure to see some weak true echoes, but one could never be sure if they were real anyway. The best choice for the level of the threshold will be a compromise depending on the importance of detecting all true targets, and the penalties associated with a false alarm, i.e. mistaking a false echo for a true target. Choice for threshold would probably lie in the range 8dB to 16dB above the r.m.s. noise level.

The ratio of the amplitude of a signal to the r.m.s. value of noise is known as the signal-to-noise voltage ratio. (The signal-to-noise ratio can also be expressed as a power ratio or in dB.) The signal-to-noise ratio is a measure of how certain we can be that the echo represents a true target.

3.3.7/ Doppler Frequency Shift

Let us consider a radio transmitter and a radio receiver located at two fixed points (stations). Suppose the transmitter sends out a signal at a frequency f and it is received directly at the other station. If the receiver measures the received frequency it will get a result f. But if one station starts to move toward the other at a velocity v, the receiver will now measure a higher frequency f + vf/c, where c is the velocity of electromagnetic radiation. It doesn't matter which station is moving, or even if both are moving, and they don't have to be moving directly toward one another. The velocity "v" is the rate at which the distance between the stations is changing, and it may be positive (net motion toward each other) or negative (away from each other). The quantity vf/c is the doppler frequency shift. See Figure 3-20.

Now, suppose the transmitter and receiver are located at the same point, the radar location, and that the received signal is a signal reflected from some object. If the object is not moving with respect to the radar location, that is, if the distance between the object and the radar is not changing, the frequency of the reflected signal is the same as the frequency transmitted. However, if the distance between the two is

changing (decreasing) at a rate of + v metres/second, the total path length travelled by the radiation from the radar to the object and back, is changing at a rate of 2v metres/second. Therefore, there is a doppler shift of + 2vf/c in this case. Again, it does not matter which moves, the radar or the object, or both. If the two are not moving directly toward one another, the effective velocity is the component of motion of one toward the other, v cos θ . See Figure 3-20. If they are moving away from one another the value of v, and of the doppler shift is negative.

A radar system intended for the measurement of doppler frequencies contains a very stable frequency source. The frequency of the transmitted pulse is generated from this, and each echo received is compared with this frequency to determine the doppler frequency shift. This comparison amounts, essentially, to multiplying cos 2 π f, representing the transmitted signal, with a cos 2 π (f + fD), representing the received, doppler shifted signal. The result is

$$1/2(a \sin 2\pi (2f + fD) + a \sin 2\pi fD)$$

which contains two components, a high frequency component of frequency 2f+£D which can be removed by a low pass filter, and a signal at the doppler frequency fD. See Figure 3-21. This description is highly simplified and the actual processing is somewhat more complex.

A number of methods can be used for the actual determination of the value of the doppler frequency, once the signal at that frequency has been isolated. These include banks of filters covering the expected range of doppler frequencies,

spectral analysis by techniques such as hardware or software implementations of the Fourier transform, or for cases where only one doppler frequency is expected, cycle counting or measurement of phase difference between two received echoes separated by a known time interval.

Some methods of determination of doppler frequency are subject to a source of error which is only one demonstration of an important source of error (or ambiguity) in many types of measurement. This is a violation of the conditions of the Sampling Theorem. Freely paraphrased, this states that, if one wishes to capture all the information inherent in the waveform of a signal, its amplitude must be sampled with a frequency at least twice that of the highest frequency component in the signal. If we sample at a lesser frequency, the conclusions we draw from examining the samples may be erroneous. The type of error we can get is known as "aliasing", whereby a signal element having one value of some characteristic (say frequency) is interpreted as having another value. For instance, in some circumstances where we are expecting frequencies between 0 and f1, a frequency of f1 + f, i.e. beyond the range of interest, may be interpreted as a frequency f or f1 - f. See Figure 3-22.

In the special situation of a radar transmitter/receiver mounted on a moving vehicle, with all potential targets fixed or moving at much smaller speeds, the doppler frequency shift of an echo depends, for a given vehicle speed, only on the angle of the target with respect to the vehicle direction. This is because the doppler shift depends on the component of relative motion of the target toward the radar (or vice versa). See Figure 3-23.

This effect can be used to measure the approximate angle to the target if we are using a wide beam non scanning system which cannot determine angle directly. A more useful function in our application would be to discriminate against echoes due to side lobes falling on very large targets (e.g. buildings) either side of the guideway. Because of their large size, or large echoing cross section, such targets, when illuminated by side lobes might appear as false targets in the main beam. However, if they are at sufficiently large angles they can be identified by their lower doppler shift compared to targets directly ahead.

An important use of doppler shift, particularly in transportation applications, is vehicle speed determination. Except in law enforcement applications, the "radar" is mounted on the vehicle and the beam is directed toward the road surface. The highest doppler shift gives the vehicle velocity. Most systems used for this purpose do not determine range, but nevertheless they are still called "radars".

3.3.8/ Radar Displays and Signal Processing

Many types of radar display have been used. These are usually presented on cathode ray tube (CRT) displays. Here we will discuss only three types, what are called types A, B and P (or PPI). Type A is similar to the presentation we have used in Figure 3-19 to illustrate noise. It is a plot of signal amplitude on the vertical scale (ordinate) against time on the horizontal scale (ordinate). The time interval shown is the time interval between transmitted pulses, so that a new display is generated for each new pulse transmitted. This presentation gives a good presentation of signal amplitude and range, but

cannot show any information on lateral position or angle, if the radar supplies this. For this reason the most common radar display is the type P, more often known as the PPI (Plan Position Indicator) display. This is a circular presentation with the radar position in the centre of the screen. Radial distance from the centre of the screen represents range. Angular position about the centre represents the position of the radar beam at the time the echo was received. The screen remains dark if no signal above threshold is received. If a signal is received, corresponding to a given range and angular position, a bright spot is produced on the screen, the brightness depending on the magnitude of the signal. The extent of the bright area in range and angle gives the extent of the area from which echoes were received; however, any part of the target which is shaded from the radar waves by other parts closer to the radar will produce no echo, so the apparent shape may be incomplete or distorted.

In the situations with which we are concerned, we are more likely to be scanning a relatively narrow angle in front of the radar, rather than a full circle of 360°. Thus, our picture would be confined to a narrow sector of the PPI display. The type B display, which gives a rectangular picture with range on the vertical scale (ordinate) and azimuth angle on the horizontal scale (abscissa) is better suited to most of our applications.

See Figure 3-24 for sketches depicting these three types of display.

In the case of a radar system using a beam which is narrow in both angular dimensions, neither the PPI or the type B display is adequate. In this case the PPI or Type B presentation

can be used for the horizontal (plan) display and an additional display, probably on the same tube , used to show the elevation (elevation angle vs range).

It should be noted that, while these presentations are images in the sense that they present a "picture" of a physical situation, unlike optical images they do not represent the situation as seen from the point of view of the observer. In the case of the PPI or B display the point of view is from above (plan) and for the elevation angle presentation (type E) it is from the side. The appearance of objects, also, differs from the appearance to the eye. Brightness of the display depends on the radar cross section of that part of the object illuminated by the radar beam, which may differ considerably from its visual impact. Also, some parts of the object which would be visible to an observer at the apparent "point of viewing", i.e. above the scene in the case of a PPI, may be shaded from the radar, and thus produce no echo.

In many radar applications display is not the important function. This is the case where processes are controlled automatically or where information is fed to a computer system for correlation or integration with other information before the information is displayed or a computer-based decision made. Examples of this would be missile borne tracking radar for missile guidance, gunnery fire-control radars, satellite tracking and counting radars, speed measuring radars and collision avoidance radar. The processing required before the information is used may be very simple, as in most tracking radars, or it may be very complex, as in integrated continental defense systems.

The type of processing required will depend both on the application for which the active vision sensor is required, and on the nature of the vision sensor and the nature of the raw data it produces. The question of signal processing is discussed in more detail in Section 5.0, but we can make some generalizations here with respect to radar sensors.

Because radar techniques are well adapted to detecting targets at moderately large ranges, and because range resolution for radar is the same for all ranges, radar techniques are well suited to obstacle detection, although there may be limitations in the ability to identify objects. On the other hand, radar is not ideal for robot control applications in maintenance or inspection. Range measurement by pulse radar becomes increasingly demanding at very short ranges because of the necessity of measuring very short time intervals. A range of six inches requires measurement of an interval of 1 nanosecond (1×10^{-9} second) which implies pulse lengths and measurement resolution of a fraction of a nanosecond. Closer measurements than this would be required for control of robot inspection, maintenance or cleaning, but they would become very difficult with pulse radar techniques.

It is true that there are other means of measuring distance in radar than by pulse delay. FM radar techniques, where a frequency difference rather than a time interval is measured to give range, could be used for very short ranges. See Section 4.0. Even CW phase measurements, essentially standing wave measurements, could be used to measure very short distances. However, there would also be problems in measuring angular

location of targets very close to the transmitting antenna at conventional radar frequencies.

It would be possible to overcome the angular resolution problem at short distances by using laser radar (sometimes called "lidar" for "light-based detection and ranging") but this is outside the coverage of this section. In any case, it seems that other techniques, such as those based on optical imaging, or on triangulation for measurement of distances, might be more suitable for short range robot guidance. The problem of target distance measurement for computer vision systems has been discussed in detail by Jarvis (6,7).

3.3.9/ Extraction of Target Characteristics From Radar Data

The determination of information about a target other than the presence and aproximate radar cross section of the target, oriented as it was at the time of the pulse transmission, is difficult. This is particularly true if the information is to be extracted and used by automatic systems.

Claims have been made for some personal detection radars, particularly those based on detection of doppler shifts, that an experienced operator can distinguish between individuals by studying the detailed characteristics (signature) of the echo. With CW doppler radar fences (e.g. the Mid-Canada Line, now out of service), under some conditions it was possible for a skilled observer to differentiate between aircraft and flights of geese. It has also been claimed that propellor aircraft can be distinguished from jet aircraft by the returns seen on conventional radar. In these cases the basis for the

discrimination is the differing relative motions of parts of a composite target.

Considering more or less static targets, the magnitude of the echo depends on the radar cross section of the target, in the particular orientation seen at the time the radar pulse struck it. This depends on the impedance mismatch presented to the electromagnetic waves travelling in air, and on the geometry of the surface. A body which presents a large difference in dielectric constant (in general, dielectric constant = (index of refraction)(2) from the surrounding air, or which has a high conductivity, will reflect electromagnetic waves strongly. Unless the geometry of the surface is such that the reflected waves are directed away from the radar (e.g. a large plane conducting sheet not approximately normal to the beam from the radar), such a body will have a high radar cross section. From the standpoint of collision avoidance, a high radar cross section probably, but not invariably, means a target large enough to represent a hazard. One exception, for instance, would be a large mass of crumpled metallic foil. Even a relatively small sheet of flat metal foil, oriented normally to the radar beam, would present a large radar cross section, but such a situation could arise only from deliberate mischief.

In some cases, if the radar transmitted and received both horizontal and vertical polarization, or transmitted on one and received both, the ratio between received signals on the two polarizations would give some clues as to the nature of the surface. This would also be true if right circular polarization were transmitted, and both right and left received. It is

doubtful that sufficient detailed information is available for the design of a reliable system of target identification.

For sufficiently large targets, target shape in the "plan" view, might be inferred from the radar returns, if the radar resolution were sufficient. This would imply the use of short wavelengths, to get narrow beamwidths and high angular resolution, and very short pulses to get high resolution in the range direction. However, as pointed out previously, there may be no returns from features of the target shaded by other features closer to the radar, and there will be none from the rear surfaces. Also, the relative importance of various features may be different in the radar image. Thus, the observed plan-view shape will be incomplete and possibly distorted.

3.4/ Radar Types

3.4.1/ General Discussion of Types of Radar

Radar systems can be classified in a number of ways, e.g. according to function, according to techniques employed, or according to the "platform" from which they are used (e.g. land based, marine, aircraft, missile, or satellite.) In the following discussions of individual types, some are functional distinctions and some are distinctions of technique, so the division into types is by no means mutually exclusive.

3.4.2/ Search Radar

Search radar is probably the most common type of radar and embraces most well known applications of radar. As the name implies, it is used when the location and even the existence of targets is not known, and its object is to detect the presence of targets and determine their location. This type of radar is used

for military purposes (e.g. warning of intruding aircraft), in ship-borne applications, for detection of obstacles, and guidance in harbors, for similar purposes on aircraft, for air traffic control using radars based at airports, and for other similar applications.

Most search radars use beams which are narrow in azimuth (horizontally) and have relatively wide vertical beams and search in azimuth, so that they detect all targets regardless of elevation (e.g. aircraft at different altitudes) and they do not provide discrimination between targets at different heights. Where altitude or angular elevation is important (as for instance in air traffic control close to an airport, or in terminal guidance at an airport) a modification of the search radar concept is used, in which the beam is narrow in elevation but relatively broad in azimuth, and scans vertically rather than in azimuth. The presentation for these is known as a range height indicator or RHI.

Search type radars frequently have the ability to measure the doppler frequency shift on the echo from a target. This may be used directly to determine the (radial) velocity of the target, but it is also useful just as a means of separating the target echo from other echoes on the screen and making it more easily detected.

The maximum range of a "search" radar can be quite impressive, given a long enough waiting time for the echo to return and sufficiently complex processing to detect very weak echoes. Echoes from planets (e.g. Venus) were detected some twenty-five years ago, and doppler imaging, using the planet's

rotation to enhance lateral resolution, is now used to obtain crude maps of surface reflectivity.

Search radars usually present their output on CRT display screens, but in some cases their signals go directly into sophisticated computer systems where complex processing and correlation with other information (e.g. aircraft flight plans, and the results of previous scans of the same area) are done before the information is finally displayed, or used in other ways.

3.4.3/ Tracking Radar

Some radars are used, not to look for targets, but to follow the motion of a target once it has been located. The initial location of the target is usually done by another search type radar, although there have been some radars which combine the two functions (track-while-scan). Tracking can be done by computers using the output of a conventional search type radar,but most tracking radars are narrow beam radars whose beams are kept directed toward the target, at least while tracking it. (Some very "agile" radars are capable of tracking more than one target at a time by jumping from one to the other, dwelling on each only long enough to measure its position and motion accurately enough to be able to return to it later). This type of tracking radar now uses four overlapping beams, two vertically and two horizontally, which cross over on the antenna boresight line, in a technique known as monopulse tracking. See Figure 3-25. Equalizing the signals in the four beams assures that the boresight points toward the target. Before the monopulse technique was developed, tracking radars used a "conical scan"

antenna, in which an antenna beam, slightly offset from the antenna boresight, was rotated about the boresight line. Signals from successive pulses were compared to give the feedback signals mecessary to direct the boresight line accuragely toward the target and to maintain it there.

Tracking radars can achieve higher signal to noise ratios on a given target than search radars because they have beams which are narrow in both angular directions, and thus have higher gain, and because they spend more time looking directly toward the target, i.e. their dwell time on the target is longer.

Tracking radars are used to direct the fire of weapons, to guide missiles toward a target, and to identify the orbits of satellites.

3.4.4/ Doppler Radar

The principle of the doppler shift in frequency, due to relative motion of the target and the radar has been discussed previously in Section 3.3.7. Many radar systems have the capability of measuring the doppler shift of echoes returned from targets, by comparing the frequency of the electromagnetic waves constituting the echo, with the frequency generated by the radar transmitter. Knowledge of the doppler shift has several uses. Basically it measures the velocity component of the target toward the radar, or of the radar toward the target. If the radar is stationary, this serves to identify a moving target, and if the track of the target is known, to measure its velocity. If the radar is moving at a known speed, e.g. on a vehicle, and the target is known to be more or less stationary, the doppler frequency will tell what the angle is between the direction of

vehicle motion and the location of the target. Also with a vehicle borne radar, if the beam is directed forward or rearward and illuminates the ground, the maximum doppler frequency shift will be a measure of the vehicle velocity.

Doppler shifts may be measured with pulsed radar or with CW (continuous wave) radar, as long as the transmitted frequency remains fixed, at least until the echo returns. See Figure 3-20. It is also possible to measure doppler shifts due to moving targets in bistatic CW "radar" configurations, i.e. where the receiver and transmitter are separated by some distance. Since CW doppler systems do not lend themselves to imaging applications, we will not consider them any further here.

The most common use for the measurement of doppler shift in fixed pulsed radar systems is for moving target indication (MTI), to distinguish moving targets from a background of more or less fixed "clutter". It is also possible, but requires more complexity, to detect, from a moving radar, objects which are moving with respect to a background of fixed clutter. This is more complex because in the case of a moving radar, even the echoes from fixed clutter show doppler frequency shifts, and it is necessary to distinguish the target doppler shift from these.

In order to detect and measure doppler shifts it is necessary to use a radar with a stable frequency reference so there is a basis for comparison when the echo returns. This was quite a problem in the early days of MTI radar, when the transmitted frequency was generated directly by a magnetron tube, with no fixed phase relationship between one pulse and the next. Various schemes were used to maintain the frequency

reference stable until the echoes returned. (e.g. Stalos, stable local oscillators and cohos, coherent local oscillators.) Conventional MTI radars use pulse to pulse phase comparison of echoes to detect doppler shits and therefore they are insensitive tc the particular value(s) of doppler shift which cause echoes from two successive pulses to have the same phase, i.e. when the doppler frequency shift is equal to the pulse repetition frequency (prf) or a multiple of it.

The problem of a stable frequency reference disappears if we use a radar system in which all frequencies are generated from a low power stable source, the higher power signals for pulse transmission being produced by amplification from the low power source, or by frequency/phase locking a high power oscillator to the low power source. Such a radar is called a coherent radar. Most modern radars fall into this category.

An important subject in analysis of the detailed performance of radar systems and their doppler capabilities is that of the ambiguity function. This is a complex subject, requiring advanced theory for its treatment, and is not felt to be essential for our present purpose. It is treated extensively in the radar literature, and the reader is referred to this, particularly to reference 8 and its bibliography.

3.4.5/ FM-CW Radar

The principle of FM-CW radar has been described in 3.3.4, as an alternate means to pulse-echo delay for measurement of target range. It is particularly well adapted to situations where the distance to a single relatively large target must be measured or controlled. Thus, it is the common technique used

for radio altimeters, and has been used for docking radar in space applications. The common modulation technique is a symmetrical triangular wave, as was shown in Figure 3-16, although saw tooth wave forms have been used. The symmetrical triangular wave has the advantage that, if substantial doppler frequency shifts are present, their effect on the apparent distance is opposite on the rising and falling sides of the modulation, and tends to cancel.

Because solid state sources can be swept over wide bandwidths at very high scan rates, it should be possible to use FM-CW radar for measurement down to very short distances. This would make it a possible candidate for distance measurement with manipulating robots. Other techniques, possibly using the same millimeter wave source would be required to provide the imaging which would also be required.

3.4.6/ Synthetic Aperture Radar and Side Looking Radar

Synthetic Aperture radar is mentionned here for completeness, since it is an important topic in modern radar, but is seems unlikely to find application in the transportation applications we are considering here.

Synthetic aperture radar takes advantage of the motion of a rapidly moving vehicle (e.g. an aircraft or a satellite) to obtain the effect of an antenna which has a very large aperture in the direction of the vehicle motion, much larger than could be actually carried by the vehicle. This requires storing the signal as the actual antenna element moves along the "synthetic aperture" with the motion of the vehicle and performing complex calculations. The effective beam from a synthetic aperture is

very narrow in the direction normal to the vehicle motion, and for this reason it is usually combined with another approach known as side-looking radar. See Figure 3-26.

In side looking radar, beam scanning is usually replaced by vehicle motion. A beam which is narrow in the fore-aft direction, but relatively broad vertically looks to one or both sides of the radar, illuminating the ground for some distance off the ground track. Range is measured by echo time delay as usual, and position along track is given by the position of the aircraft at the time of pulse transmission/echo reception. The system is not sensitive to roll of the aircraft, but must be corrected for aircraft yaw and to a leser degree, pitch. Side looking radars may use either conventional antennas (e.g. SLAR, sidelooking array radar) or synthetic aperture antennas.

Side looking radars, and particularly those using synthetic aperture antennas, produce very detailed images of the terrain to the side of the track, but because they are limited to examination of the situation at the side rather than in front of the vehicle, they seem inappropriate to our present interests.

The synthetic aperture principle can be related to a more general approach called range-Doppler radar which is covered briefly in the next section under "Imaging Radars".

3.4.7/ Imaging Radars

Most radars can produce "images" in the sense that they can give a presentation in which the relative positions of different objects are represented on a screen. However, as has been mentionned previously, the viewpoint in such images is not that of the radar position, but above, and generally at some

distance, in the case of PPI presentations, or to the side in the case of RHI presentations. Thus, the images are in no way similar to the image which would be seen by an optical camera at the location of the radar. This does not, of course, imply that they are not useful in the applications we are considering; in fact, the availability of range as one of the co-ordinates of the image should be advantageous in many cases.

There have been great advances in radar type imaging in the past twenty years. We have already mentionned side looking radars and synthetic aperture radars. The latter turns out to be one of a class of radar approaches which makes use of the presence of a gradient in doppler shift across the image, such as might be obtained by rotating the target, or moving the radar past the target, so the target was seen from different angles and different parts of the target had different relative motions with respect to the radar. The general technique is known as range-Doppler imaging because the image is segregated into lines of constant range and lines of constant doppler, which are orthogonal. A recent tutorial article (Ref. 9) describes these developments, the underlying theory and some of the achievements in this field, and gives an extensive set of references. Unfortunately, the application of these developments to the situations we are considering does not seem very promising. The basic requirement of a component of angular motion of the target with respect to the radar is missing in situations in which we are interested.

It is quite possible to obtain a true camera like image using radar wavelength electromagnetic radiation, the difference

between light waves and radar waves being only a matter of scale, light waves being shorter in wavelength by a factor of 10^3 to 10^5. However, except at very short millimeter wavelengths the lens and other components of the camera would be prohibitively large, and even then the resolution in the picture would be low. Nevertheless, using a CW source of short millimeter wave radiation, a lens and an array of detectors it is possible to obtain a true optical millimeter wave image. Such an image, like any optical image, lacks direct range information. Its intensity variation represents millimeter wave reflectivities rather than visible light reflectivities. Its only potential advantage over visible lightimaging lies in a greater ability to penetrate fog, snow, and, perhaps, rain.

Such an image has other differences from a conventional visible light image, due to the coherent nature of the source. In fact, it has much in common with a visible image in laser light. The phenomenon of speckle, due to interference between radiation reflected from different parts of the target, is observed in both. This results in a time varying graininess of the image. It can be partly eliminated by averaging a number of successive pictures.

The limited amount of work which has been done on optically imaging millimeter wave systems is discussed by Gordon, Hartman and Kruse, in Reference 10 . Atmospheric effects, system design considerations, tradeoffs and image quality are discussed. A very grainy but just recognisable picture of a tank using 3.2mm radiation is given.

The optical imaging technique discussed in the above

paragraphs does not use radar ranging. An interesting possiblity would be the combination of the optical imaging with the use of radar type ranging (either echo-delay or FM type ranging) for selected points on the image.

3.5/ Millimetre Wave Radar

3.5.1/ General

Millimeter wave radar does not differ in its basic principles from radar at any other frequency, so what we have to discuss here is those characteristics peculiar to radar applications at millimeter waves, which may affect use in transportation applications.

The term millimeter waves is a rather vague designation for electromagnetic waves of less than 1 centimeter wavelength, the exact range varying with the source quoted. The most reasonable definition seems to be wavelengths from 1 centimeter (30 Gigahertz) to 1 millimeter (300 Gigahertz). Other equally indefinite terms are "near millimeter wave" (NMMW), say, from 100 GHz to 1000 GHz, "submillimeter waves". 150 GHz to 3000 GHz and "extremely far infra red" about the same range as for submillimeter waves.

3.5.2/ Characteristics of Millimetre Waves

From our standpoint, those characteristics of millimeter waves which make them desirable for use in radar are the following:

1) Due to the short wavelenths, an antenna of a given size gives a much narrower beamwidth (see Section 3.3.2). This means a greater angular resolution in the image, whether it be a plan image, or an optical image.

2) Due to the high frequency, large bandwidths can be easily obtained. This makes short pulses, and high resolution in the range direction possible. (This would normally only be a problem at quite low radar frequencies, below, say 1 GHz).

3) Compared to frequencies in the submillimeter region, or extremely far infrared, millimeter waves are easier to generate with reasonable power levels, easier to detect, and can be handled more easily in waveguide type circuitry and are less sensitive to atmospheric effects and precipitation. (On the other hand, compared to lower frequencies, they are poorer in each of these categories.)

There are also a number of disadvantages to the use of millimeter waves. Generally, these are stated in comparison to the corresponding behaviour of longer electromagnetic wavelengths.

1) Attentuation (loss of signal strength) due to atmospheric absorption, fog, rain and snow becomes more significant in the millimeter wave region. At wavelengths of 3 cm or higher it is generally negligible.

2) Scattering due to fog, rain, snow is more significant in the millimeter wave region, giving rise to the possibility of "false" indications in an obstacle detection radar.

3) Attenuation of waveguide used to transmit signals from point to point within the radar is higher at millimeter wavelengths. Special means, which introduce other problems, have to be used to reduce this.

4) Millimeter wave receivers cannot be made of as good quality, in terms of "noise figure" as at lower frequencies.

5) Manufacturing tolerances have to be much less for millimeter wave antennas and circuitry, resulting in higher costs.

6) It is much easier to generate higher powers at lower frequencies. However, there have been considerable improvements in the generation of low to medium power levels by solid state devices.

3.5.3/ Millimetre Wave Imaging

The fact that the list of disadvantages given above, is longer than the list of advantages, should not be taken as an indication that millimeter wave radar is unsatisfactory for our purposes. For an imaging application,, whether it be plan imaging or optical imaging, high resolution is of paramount importance, and only the use of millimeter waves (as opposed to other "radar" wavelengths) offers high resolution with reasonable size of the antenna and other components, since we cannot use such techniques as delay-doppler imaging to enhance resolution.

Even at millimeter wave frequencies angular resolution will be a problem in obstacle identification from the vehicle itself. With a two-metre antenna, at 1 mm wavelength, the beamwidth would be of the order of 1/2000 of a radian. However, this cannot be taken as representing 10 cm at 200 metres, since the concept of angular beamwidth is not valid for distances less than $(\text{antenna width})^{(2)}$ divided by wavelength, or 4000 metres in this case. At ranges less than this the beam behaves more like a projection of the antenna aperture size, i.e. a "parallel" beam almost 2 metres in width. See Figure 3-27. Details within this beamwidth cannot be distinguished. From this standpoint one would be better off with a 20 mm antenna at a wavelength of 10

microns, i.e. CO2 laser wavelength, which would give the same angular beamwidth but a smaller spot size at short distances.

One unconventional approach which should allow us to produce a spot size considerably smaller than the antenna width would be to use an antenna focussed at a particular relatively large distance, rather than a conventional antenna producing a nominally parallel beam (i.e. focussed at infinity). See Fig. 3-28. Using a horn fed reflector this would mean using an elliptical reflector rather than a parabolic one, although an approximate result could probably be obtained by merely repositioning the feed horn. A thin dielectric phase adjusting lens against the parabolic surface could also be used. With a 2 metre antenna aperture focussed to produce a 'spot' at 0.5 kilometres, it should be possible to get a spot size of approximately 0.3 metres over a distance of about 0.35 km to 0.65 km. Using this approach, the antenna focussing must be designed to produce minimum spot size at a particular distance, and will be effective only over a limited range of distances about that point. The far distance performance of such an antenna would not be as good as an unfocussed aperture, i.e. one having constant phase over the whole aperture.

From the standpoint of optical imaging the lateral dimensions of the spot size are the only significant factors in resolving details in the image, but with plan imaging we also have range resolution. In radar, range resolution is determined by the pulse length, and is about 0.15 metres per nanosecond of pulse length. A pulse length of 10 nanoseconds is about the shortest we could expect. This would correspond to 1.5 metres resolution. It is not dependent on distance.

Thus, even using millimeter waves, the image resolution obtainable will only be adequate for the identification of quite large objects even at distances of no more than 0.5 kilometre. Studies have indicated that, for a reasonably high probability of recognition of an object, the size of the object should be from 4 to 8 times the minimum system resolution (10).

One possibility that has not been considered is that of combining optical imaging with range determination by echo delay timing using pulsed transmissions or by use of FM on a CW transmission. This would give a three dimensional 'image' which might assist in object identification. The means of using this additional information in image analysis processing would require study.

In the imaging systems we have been discussing, the plan type imaging would most likely be carried out using a scanning beam and a single detecting system, and it, of course, uses a pulsed transmission for echo delay measurement. Optical type imaging could be done using a single scanning beam, but would most likely use an array of detectors, either a two dimensional array, or a linear array with scanning in the other dimension, which would amount to scanning a one dimensional array of beams. If using an array of detectors the object area would be illuminated by a separate transmitting antenna.

3.5.4/ Millimetre Wave Radar Performance

The radar equation mentionned previously can be re-arranged and modified by introducing terms for various losses etc., to give

$$P = (64\pi^3 KTR^4 BFSL/G^2\lambda^2\sigma)10^{0.2\alpha R}$$

where P = peak power required to give maximum range, R,

for given conditions

R = maximum range for peak power ,P, and other conditions given.

λ = wavelength

B = receiver bancwidth, assumed to be approximately 1/ pulse length

G = antenna gain

= target radar cross section

K = Boltzmann's constant, 1.38 x 10-23 joule/degree K

T = reference temperature (290° K)

F = receiver noise figure

S = minimum signal-to-noise ratio required for detection

L = system losses

α = atmospheric attenuation coefficient for wavelength λ

$64\pi^3KT = 7.94 \times 10\text{-}18$ joules

In Table 3- 1 we compare four sets of radar parameters, determining the value of P, the power required for a 3 kilometer range, for each. In each case, the parameters chosen are considered reasonable for the wavelength used. In all cases, the antenna is circular, 1 metre in diameter. A target cross section of $0.1m^2$ is assumed. Also it should be noted that in all cases a pulse width of 20 nanoseconds is assumed, leading to the bandwidth of 50×10^6 Hz (50 Mhz) if the receiver is designed to match the pulse width. This means that, if we assume a pulse repetition rate of 10,000 pulses per second (pps), the duty cycle is 1/5000. The average power in each case is the peak power multiplied by the duty cycle. We have also calculated the

Parameter \ Set	1	2	3	4
Wavelength, λ(mm)	30	3	2	1
Range, R(Km)	3	3	3	3
Bandwidth, B(Hz)	50×10^6	50×10^6	50×10^6	50×10^6
Antenna Gain, G	3.2×10^3(35dB)	3.2×10^5(55dB)	7.2×10^5(59dB)	3×10^6(65dB)
Cross Section σ(m^2)	0.1	0.1	0.1	0.1
Noise Figure, F	4(6dB)	10(10dB)	30(15dB)	100(20dB)
Requires S/N, S	20(13dB)	20(13dB)	20(13dB)	20(13dB)
System Losses, L	4(6dB)	6.3(8dB)	8(9dB)	10(10dB)
Atmospheric Attenuation, α(dB/Km)	0,02	0.3	2	10
Atmospheric loss (dB)	0.06	1.8	12	60
Calculated value of required peak power (watts peak)	1.14×10^4	675	1.19×10^4	7×10^8
Average power (watts) (20ns pulses, 10,000 pps.)	2.28	0.135	2.38	1.4×10^5

Table 3.1/ Required Power for a Target Detection Range of 3 km

atmospheric loss separately in each case to show what effect it had on the final power requirement. Table 3-2 shows the result if the required range is reduced to 0.5 Km, everything else remaining the same.

These figures illustrate some important considerations in choosing the operating wavelength for a millimetre wave system.

1) With shorter wavelengths, for the same antenna size, the required power decreases as the square of the wavelength, if all other parameters are constant.

2) The use of wavelengths shorter than 3 mm implies heavy penalties in power required, if ranges of a kilometre or more are needed. This more than offsets the improvement mentionned in item (1). The penalties in going from 3 mm to 2 mm are less severe than those in going from 2 mm to 1 mm.

3) With shorter wavelengths we can expect some increases in noise figure and in system losses, which may offset the improvement mentionned in item (1). These factors are dependent on the state of technology and there may be improvements in the state of the art.

It should also be noted that it is more difficult to generate the same power level at shorter wavelengths. This is again a technological limitation, subject to change.

3.6/ Atmospheric and Other Effects

3.6.1/ Atmospheric Attenuation

Because "clear" air does not absorb significant amounts of either visible light or common radio waves we do not normally think of atmospheric attenuation as important. However, for both infrared radiation and millimeter waves it is very significant, sufficient to render a large part of the electromagnetic spectrum

Parameter \ Set	1	2	3	4
Wavelength, λ(mm)	30	3	2	1
Range, R(Km)	0.5	0.5	0.5	0.5
Bandwidth, B(Hz)	50×10^6	50×10^6	50×10^6	50×10^6
Antenna Gain, G	3.2×10^3 (35dB)	3.2×10^5 (55dB)	7.2×10^5 (59dB)	3×10^6 (65dB)
Cross Section σ(m^2)	0.1	0.1	0.1	0.1
Noise Figure, F	4(6dB)	10(10dB)	30(15dB)	100(20dB)
Requires S/N, S	20(13dB)	20(13dB)	20(13dB)	20(13dB)
System Losses, L	4(6dB)	6.3(8dB)	8(9dB)	10(10dB)
Atmospheric Attenuation, α(dB/Km)	0,02	0.3	2	10
Atmospheric Loss (dB)	0.02	0.3	2	10
Calculated value of required peak power (watts peak)	8.8	0.37	0.92	5.4
Average power (watts) (20ns pulses, 10,000 pps.)	1.76×10^{-3}	7.4×10^{-5}	1.84×10^{-4}	1.08×10^{-3}

Table 3.2/ Required Power for a Target Detection Range of 0.5 km

between visible light (wavelengths below 10^{-6}m) and common radar frequencies (wavelengths above 3 x 10-2m) useless for any significant distances in the atmosphere. Fortunately, at wavelengths above about half a millimeter (5 x 10-4 m) and at wavelengths below about 30 micrometers (30 x 10-6 m), there are a number of 'atmospheric windows' i.e. wavelength regions in which the attenuation, although not absent is low enough for use to be made of these regions in some communications and radar applications. A plot of clear weather atmospheric attenuation is given in Figure 3-29.

The attenuation of clear air is mostly due to oxygen and water vapor, with some bands due to carbon dioxide in the infrared region. The oxygen content of the air is essentially fixed, but the water vapor content varies considerably from time to time and place to place. Thus, the amount of absorption represented by the peaks labelled H_2O, i.e. their height on the diagram, will vary with the humidity. The values shown in the diagram represent an intermediate humidity level ($7.5g/m^3$). (Note that the H_2O peaks in this curve give the effect of gaseous water, i.e. water vapor or humidity, not of fog, rain or snow. These will be treated later). Other gases, not normally present in the atmosphere, might cause additional significant attenuation if they were present in sufficient concentration over the radar path.

The effect of attenuation on millimeter wave radar depends on the target range with which we are concerned. The signal must travel twice the distance to the target, i.e. there and back. If the target range of interest is up to fifty metres, even 10dB/km of attenuation has little effect. The required power

would be increased by a factor of 1.25 (i.e. +1 dB). On the other hand if we wish to look at targets up to 3 km, attenuation of 10 dB/km will increase the required power by the enormous factor of 10^6 (i.e. 60 dB). (This is in addition to the increase due to range, which, because of the R^4 factor, is 70 dB in going from 50 metres to 3 km, everything else being constant).

Combining the attenuation information in Figure 3-29 and calculations from the radar equation we see that for very short ranges, the basic required power will be so low that even very large attenuations, of over 100 dB/km, would cause no problem except perhaps because the dynamic range of signals from different distances will be exaggerated. At ranges of 1 km or more, however, wavelengths shorter than 2 mm will give rise to very high power requirements, and wavelengths shorter than 0.8 mm seem completely out of the question (until we reach wavelengths below 30 micrometers in the infrared, where attentuation drops again).

So far we have dealt only with the effects of invisible gaseous components of the atmosphere. In the following sections we deal with various forms of precipitation and other airborne material.

3.6.2/ Rain, Snow and Fog

Rain, and precipitation in other forms, can have two effects on the operation of a radar system. As indicated by some of the curves in Figure 3-29, rain and fog can cause attenuation which is dependent both on frequency (wavelength) and on the heaviness of the rain, or density of the fog. Also, as indicated by the fact that precipitation is visible to the eye, there is

backscatter from various forms of precipitation which depends on the density of the precipitation, its nature, and the wavelength. Through this backscatter, precipitation may cause appearance of "false" targets on the radar or may mask the presence of other real targets (i.e. significant obstacles.)

The experimental correlation of rain rate with attenuation has proven a very difficult field despite many extensive measurement programs. This seems largely due to the variable nature of rain. Theoretical treatments have not helped much in providing a reliable means of predicting rain attenuation. Therefore, the curves of Figure 3-29 can only be taken as approximations. Fog is somewhat easier to treat and Figure 3-30 gives some curves of attenuation per g/m^3 of water (or ice) in the fog for a range of wavelengths in the millimeter and submillimeter region.

It can be seen that, from the standpoint of attenuation, very light rain and normal fog will not cause serious problems, compared to normal atmospheric attenuation at wavelengths below 1 mm. Heavier rain or very dense fog may cause problems for ranges of 1 km of more. It should be noted that Figure 3-29 indicates that for rain, performance in the infra red and visible should be approximately the same as for the millimeter wave region, while for fog, the millimeter wave region is very much better.

Figure 3-31 shows the results of some backscatter measurements on rain of various intensities at various frequencies. These are obviously subject to the same measurement uncertainties as the attenuation data. These have to be

interpreted in terms of the resolution cell of the radar, i.e. the values given have to be multiplied by the volume defined by the solid beam angle, and by the length of the radar pulse, using 1 nanosecond equals 0.15 metres. The conclusion would be that for the ranges, pulse lengths and beamwidths we are dealing with, rain scattering will present no problem, except perhaps at the most extreme densities, if the scattering is no worse that the values given. Note however that wavelengths below 3 mm are not covered, although the results indicate that 3 mm scattering is less than at 4 mm. It can be safely assumed that fog will be no problem, from this standpoint, at millimeter wave frequencies.

Snow is not explicitly covered in most of the references cited. It can be safely assumed that dry snow will be no problem, but wet snow has been shown to produce attenuation at 8.6 mm wavelength which is as much as 2-1/2 times that due to an equivalent water deposition rate falling as rain. This is partly offset by the fact that snow falls tend to be much lighter, in terms of water deposition rate, than rains. It is difficult to extrapolate these results to shorter millimeter wavelengths.

Figure 3-32 gives calculated performance curves for a 2 mm radar with a relatively small antenna (10 cm) and low power source (2.5 W peak), under clear conditions and with 3.2 dB/km of rain attenuation (moderate rain). This is adapted from reference 11. The target is the size of a small truck (30 m^2). We can take the requirement for detection as 13 dB.

The radar equation, from which these curves are derived, can be reduced, for this purpose, to the following form , (in dB),

$$(S/N)_{R,d} = (S/N)_{Basic} - 40 \log R - 2 \alpha R$$

where

$(S/N)_{R,d}$ is the final calculated signal/noise ratio

$(S/N)_{Basic}$ is the signal to noise ratio calculated using the assumed parameters and unit range,

= 10log10(P6 2 /64 3KTBFL)

R is the range

α is the attenuation in dB per unit distance (using the same units of distance as R)

Thus, the form of the curves will be the same for any value of (S/N)Basic, i.e. for any combination of radar parameters. Only the values of S/N on the ordinate scale will change. It can be seen from the comparison of the two curves that the effect of attenuation due to rain increases with range.

3.6.3/ Airborne Objects

It is also possible to have effects on radar due to other objects or materials than water, suspended in, or carried by, the air. This could include dust, smoke, chemical fogs, insects, birds and objects light enough to be carried through the air. In most cases the effect would be to produce clutter or

false targets, but in the case of smoke or chemical fogs attenuation would be a factor.

Very little concrete information is available on these factors, although what there is tends to indicate that dust, smoke and chemical fogs are unlikely to cause either serious attenuation or significant scattering.

Swarms of insects have often been considered a possible cause of unexplained echoes on millimeter wave radar. Birds can certainly be detected by radar at all frequencies. Objects light enough to be carried through the air are not likely to appear as radar targets unless they have conductive surfaces (e.g. unless they are metallized). A large mass of crumpled metallized mylar film, or a metallized mylar balloon, such as sold in shopping centres or amusement grounds, might create a substantial "false" target. Such an object blowing freely through the air would cause little problems because it would appear only for an instant, unless blown directly down the guideway, but if a metallized balloon were caught on a wayside post, or on the guideway itself it might be more serious. Another possibility that cannot be ignored is that of deliberate mischief.

The general conclusion concerning insects, birds and airborne objects is that, because of the transitory nature of any "false" targets, they are unlikely to be a problem, barring deliberate mischief.

3.6.4/ Interference

In dealing with sensitive electronic equipment, one must always consider the possibility of interference. However, because of the high frequencies (short wavelengths) we are

dealing with, as well as the narrow beamwidths, direct interference at the radar frequency is unlikely. Any equipment to be mounted on a locomotive or equivalent, will be subject to a high level of interference at lower frequencies and will have to be well shielded to prevent leakage of this interference into sensitive circuits. This should offer no difficulties, since the problems of equipment design for locomotive environments have been satisfactorily solved for many applications.

3.7/ Conclusion

We have reviewed the field of microwave and millimeter wave radar, covering the basic operating principles and current state of development. Microwave (and millimeter wave) radar is more highly developed than the other detection techniques based on echo time delays, ultrasonic (sonar) detection and laser radar, and many of the techniques used in these fields were first used in microwave radar. The effects of both clear air attenuation and precipitation have been analysed although available date on precipitation (and fog) is incomplete.

For transportation applications, using radar systems with antennas of reasonable size, wavelengths in the centimeter or millimeter range, from 30 mm to about 1 mm offer good detection performance for ranges of the order of half a kilometre on 'person sized' targets, although 2 and 3 mm systems show some advantage (in lower power) even at this short range. At longer ranges, 1 mm systems rapidly become unusable because of atmospheric attenuation,

and at 3 km, the 3 mm system seems the best of those analysed. Up to 1 km rain, fog and snow are not expected to produce serious effects.

Identification of the nature of a target, beyond the fact that it reflects the radar waves, is difficult. Resolution with reasonable sized antennas is not sufficient for good imaging.

3.8/ References

The following sources have been identified by number in the text with reference to particular statements. In addition, it is pointed out that references 5, 12, and 13 are good general references in the fields of antennas, radar and millimeter waves and should be consulted for further details on the subjects discussed in this Section.

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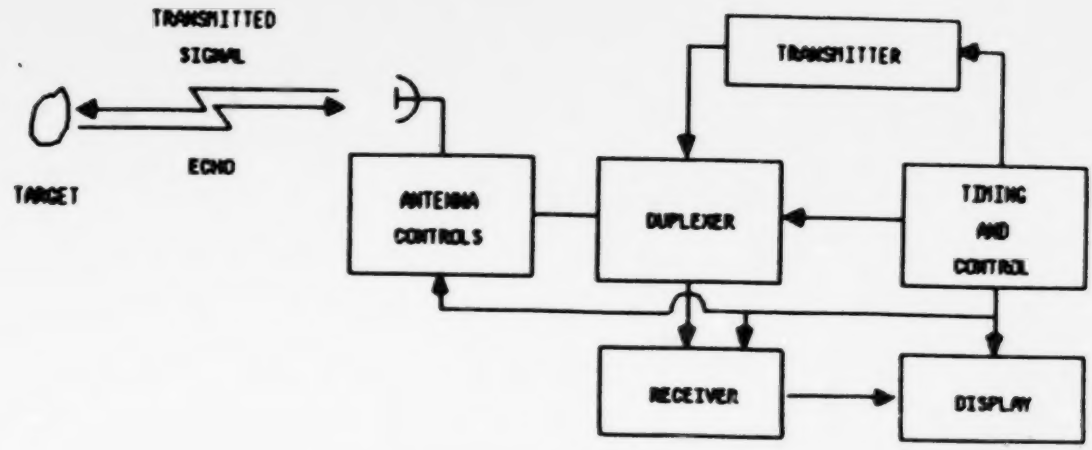
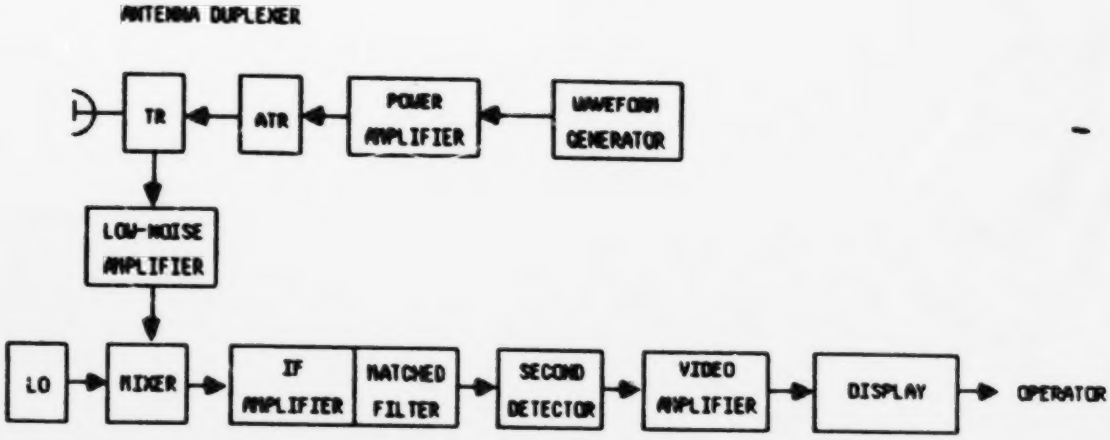
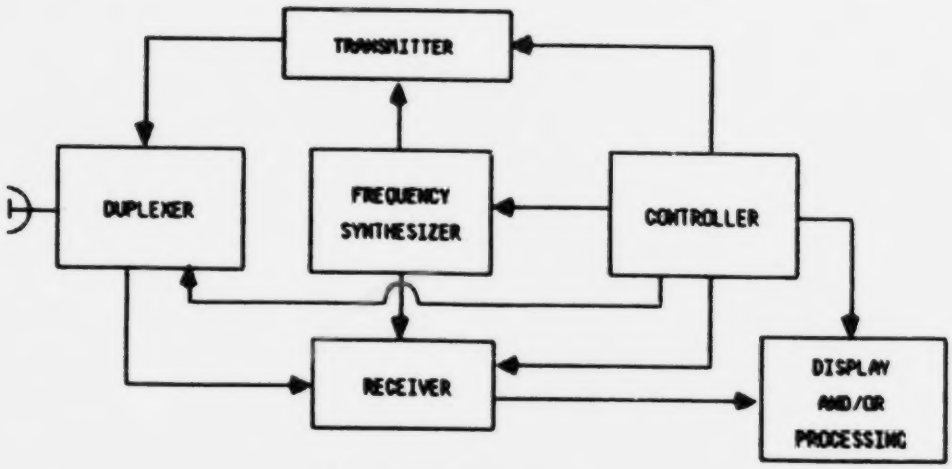
13. Button, K.J., and Wiltse, J.C., Millimeter Systems, Vol. 4 of Infrared and Millimeter Waves, Academic Press (1981). Volumes 9 and 10 of this series Millimeter Components and Techniques, Parts I and II (Button, K.J.,) are also useful.



RADAR SYSTEM FUNCTIONS

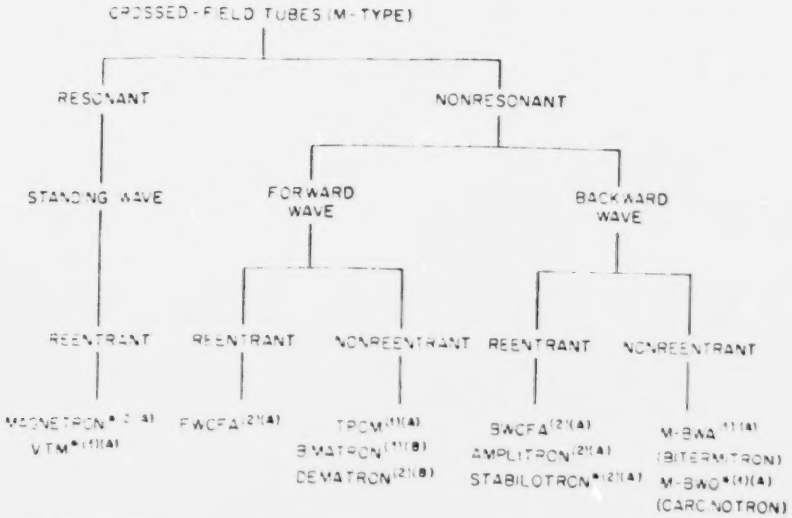


CONVENTIONAL RADAR



COHERENT RADAR

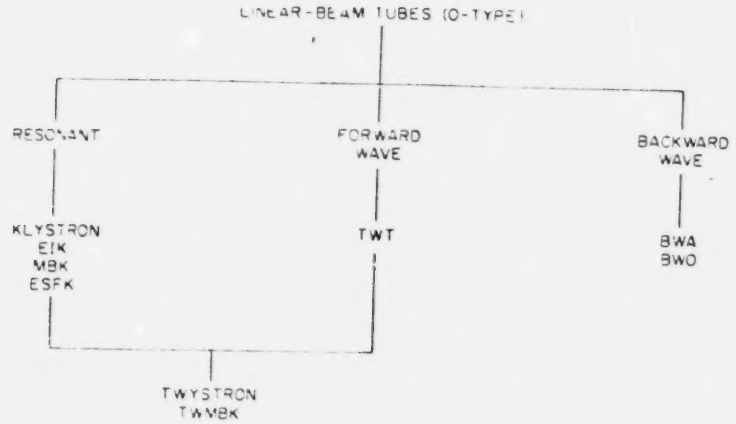
Figure 3.1/ Typical Radar Systems



* OSCILLATOR
(1) INJECTED BEAM
(2) DISTRIBUTED EMISSION
(A) CIRCULAR
(B) LINEAR

VTM	- VOLTAGE-TUNABLE MAGNETRON
FWCFA	- FORWARD-WAVE CROSSED-FIELD AMPLIFIER
TPDM	- INJECTED-BEAM FORWARD-WAVE CFA MADE BY CSF
BWCFA	- BACKWARD-WAVE CROSSED-FIELD AMPLIFIER
M-BWA	- M-TYPE BACKWARD-WAVE AMPLIFIER
M-BWO	- M-TYPE BACKWARD-WAVE OSCILLATOR

Figure 3.2/ Crossed Field Microwave Power Tubes



ESFK	- ELECTROSTATICALLY FOCUSED KLYSTRON
EIK	- EXTENDED-INTERACTION KLYSTRON
MBK	- MULTIPLE-BEAM KLYSTRON
TWMBK	- TRAVELING-WAVE MULTIPLE-BEAM KLYSTRON
TWT	- TRAVELING-WAVE TUBE
BWA	- BACKWARD-WAVE AMPLIFIER
BWO	- BACKWARD-WAVE OSCILLATOR

Figure 3.3/ Linear Beam Microwave Power Tubes

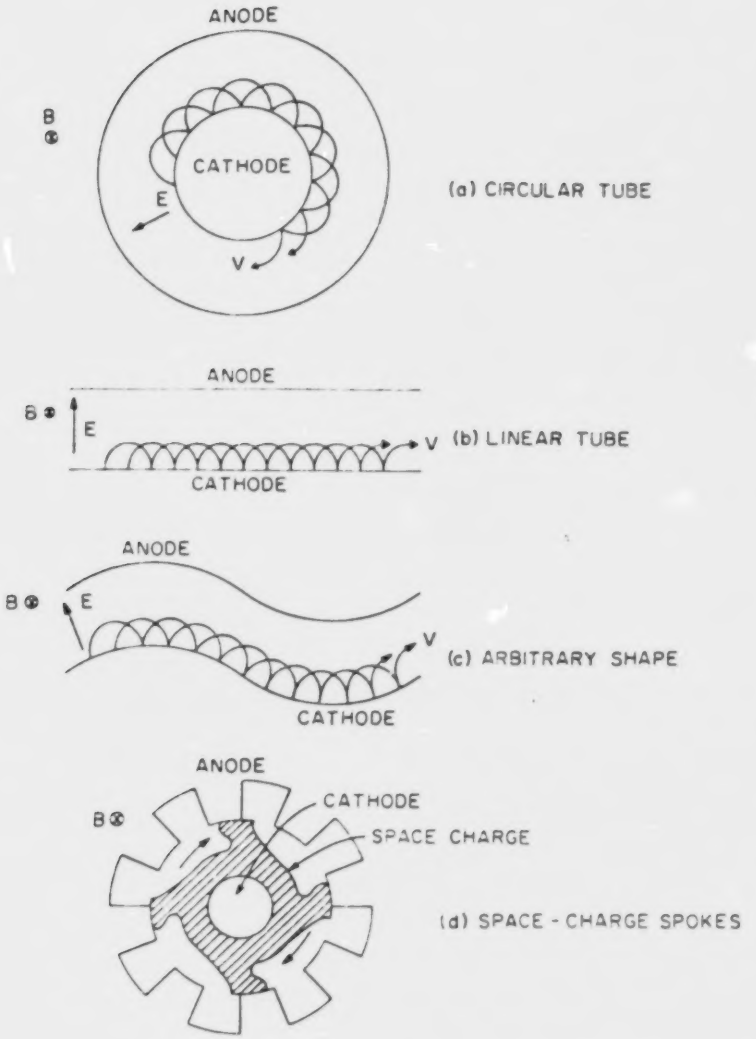
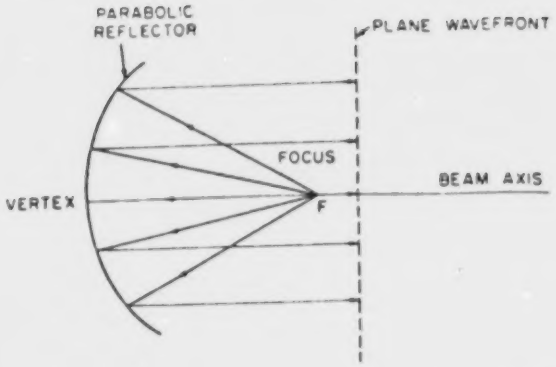
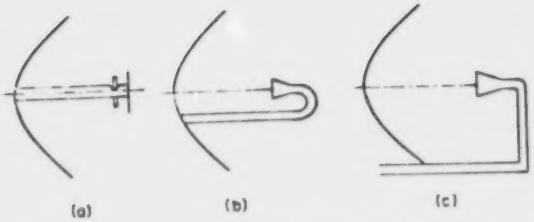


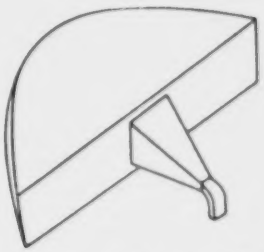
Figure 3.4/ Electron Paths in Crossed Field Tubes



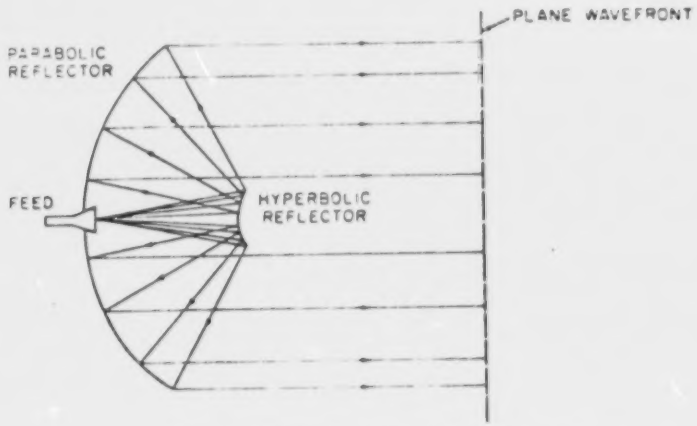
Principle of operation of a paraboloidal antenna.



Examples of the feed installations in a paraboloidal reflector. (a) Rear-feed method for a dipole-disk feed; (b) rear-feed method for a horn; (c) front-feed method for a horn.

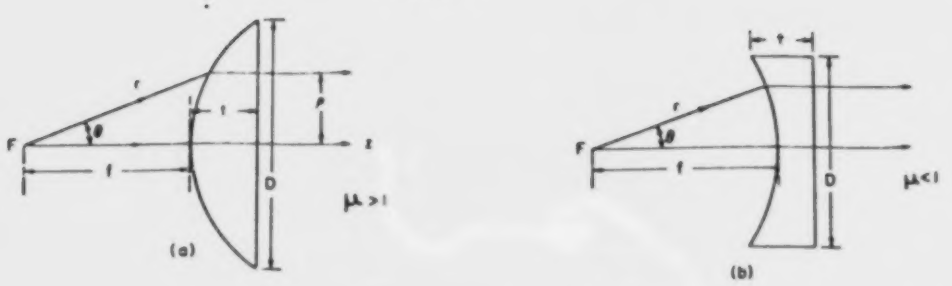


Schematic diagram of a pillbox antenna.



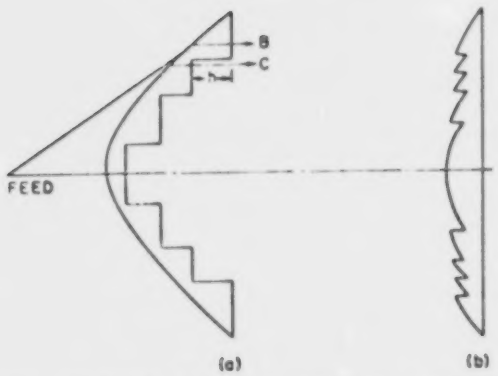
Schematic diagram of a Cassegrain reflector antenna.

Figure 3.5/ Parabolic Antenna Variations



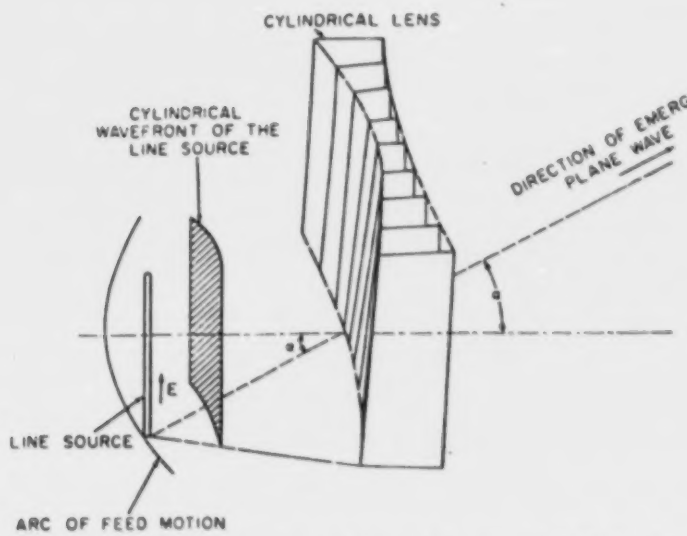
Geometry of simple converging lenses. (a) $\mu > 1$; (b) $\mu < 1$.

μ = INDEX OF REFRACTION

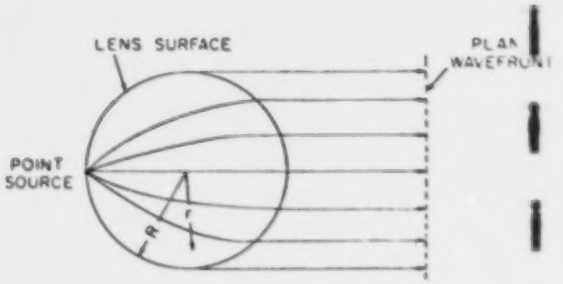


Zoned lenses. (a) Zoning of a nonrefracting surface; (b) zoning of a refracting surface.

Constrained metal-plate lens. (*After Kock.*)

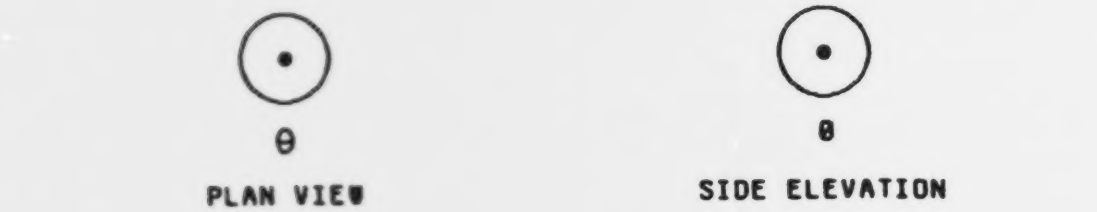


Cylindrical constrained metal-plate lens. (*After Ruze.*)



Luneburg lens.

Figure 3.6/ Lens Antenna Variations



OMNIDIRECTIONAL PATTERN

FAN BEAM

PENCIL BEAM

Figure 3.7/ Antenna Patterns
(Plan view is azimuth pattern; elevation pattern is side elevation view in the plane of the maximum gain of the azimuth pattern.)

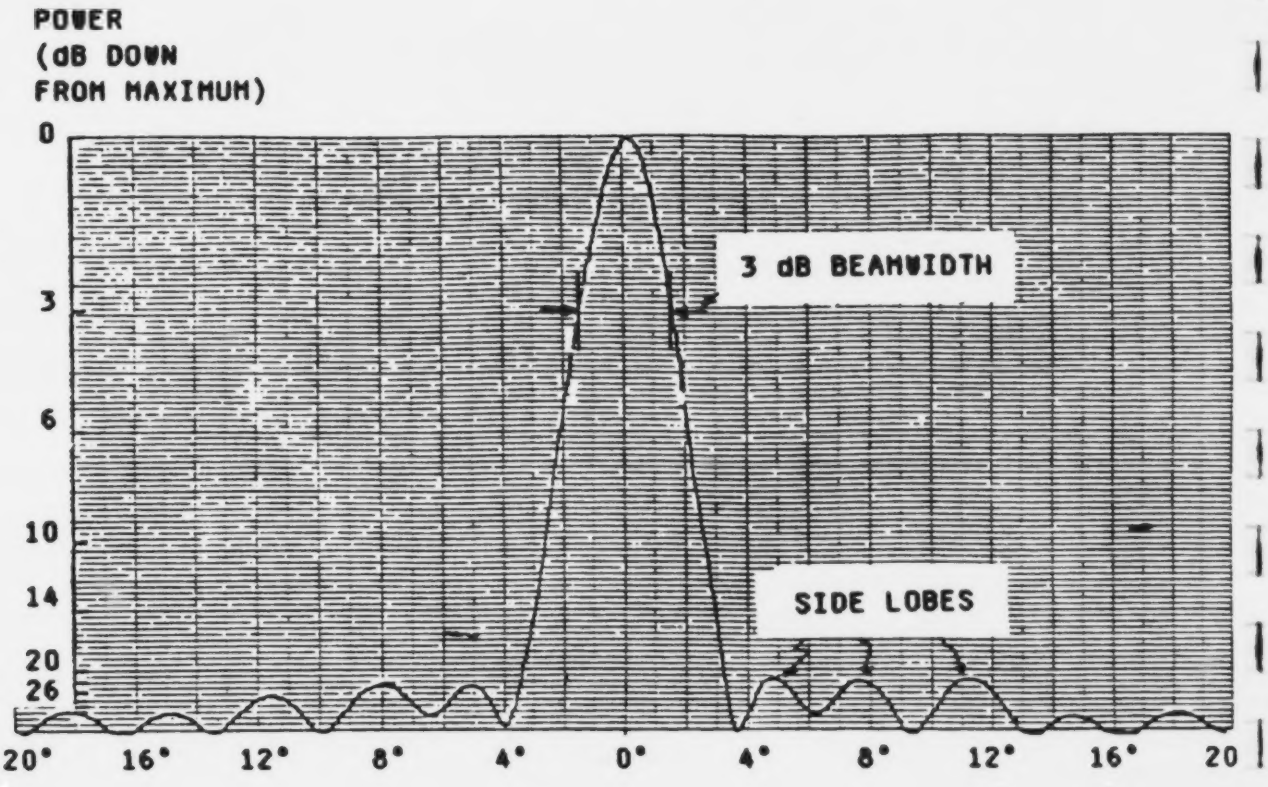
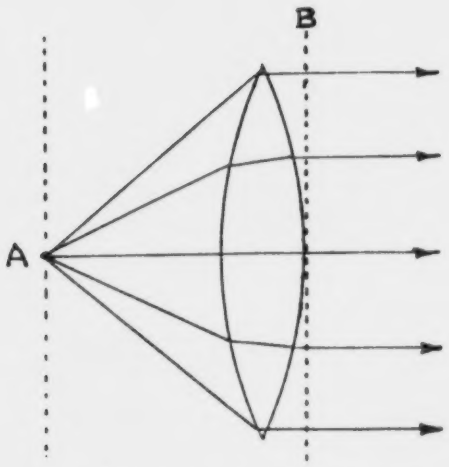
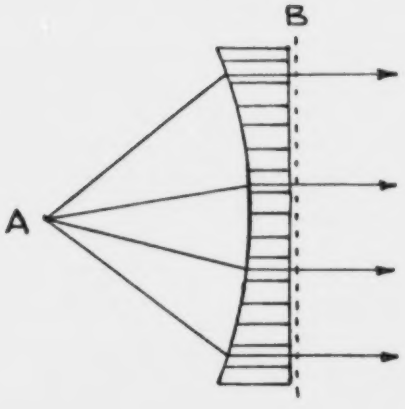


Figure 3.8/ Antenna Pattern Terminology

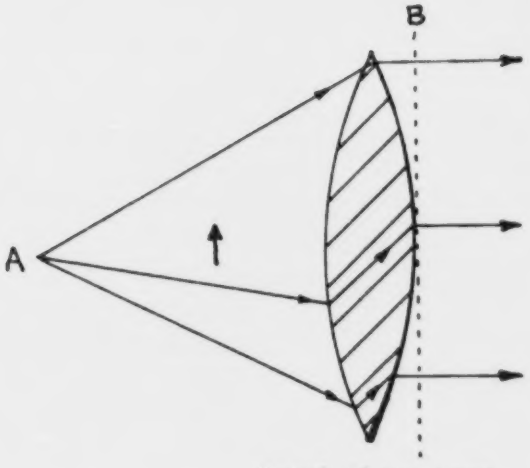


Dielectric Lens
μ is greater than 1

All paths from point A to line B are equal in optical length. Optical length of paths in the lens is μ times the actual length. Outside the lens optical length = actual length.
μ = index of refraction of the dielectric of the lens.
A is called the focus.



Metal Plate Lens
Polarisation perpendicular to plane of paper
μ is less than 1



Metal Plate Lens
Polarisation in plane of paper as shown by arrow.

Figure 3.9/ Lens Antenna

Figure 3.10/ Principle of Phased Array

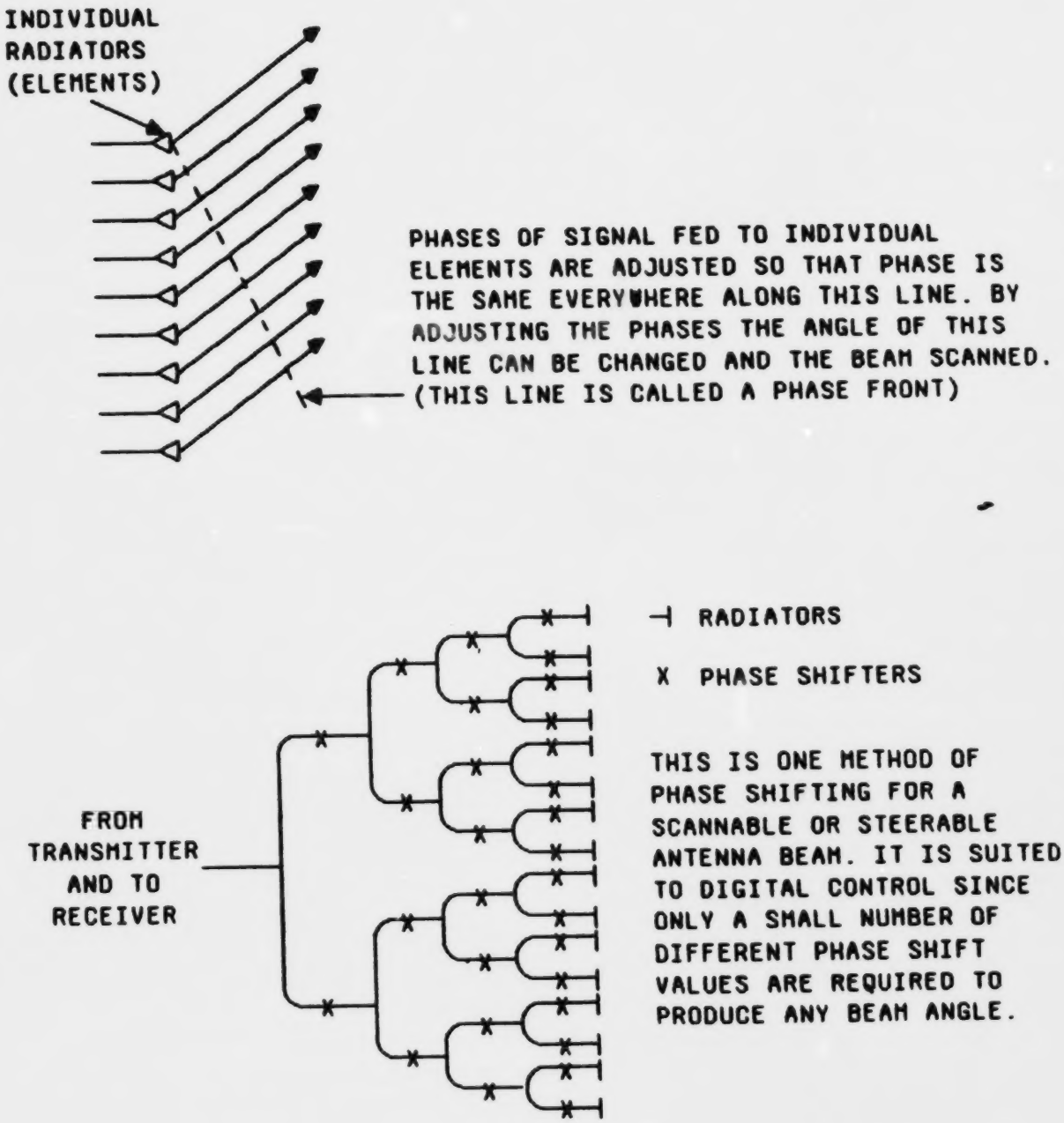
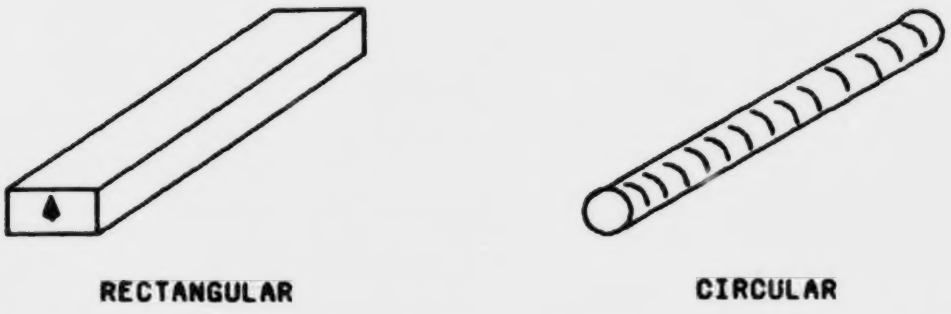

INDIVIDUAL
RADIATORS
(ELEMENTS)
PHASES OF SIGNAL FED TO INDIVIDUAL ELEMENTS ARE ADJUSTED SO THAT PHASE IS THE SAME EVERYWHERE ALONG THIS LINE. BY ADJUSTING THE PHASES THE ANGLE OF THIS LINE CAN BE CHANGED AND THE BEAM SCANNED. (THIS LINE IS CALLED A PHASE FRONT)
FROM
TRANSMITTER
AND TO
RECEIVER
RADIATORS
X PHASE SHIFTERS
THIS IS ONE METHOD OF PHASE SHIFTING FOR A SCANNABLE OR STEERABLE ANTENNA BEAM. IT IS SUITED TO DIGITAL CONTROL SINCE ONLY A SMALL NUMBER OF DIFFERENT PHASE SHIFT VALUES ARE REQUIRED TO PRODUCE ANY BEAM ANGLE.

Figure 3.11/ Scanning with Phased Rays



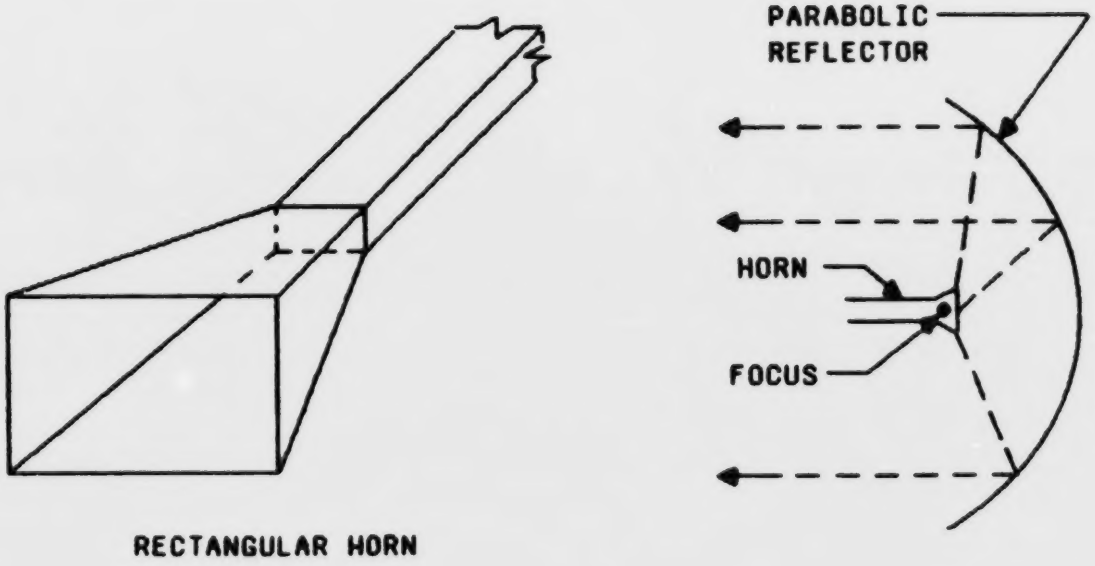
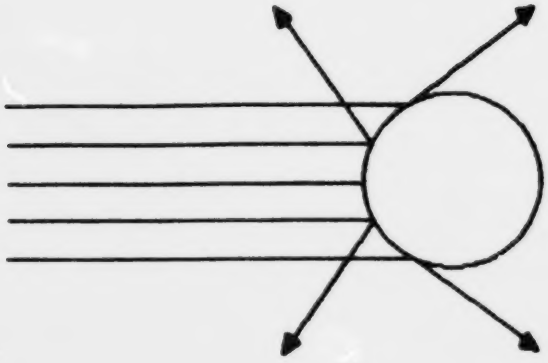
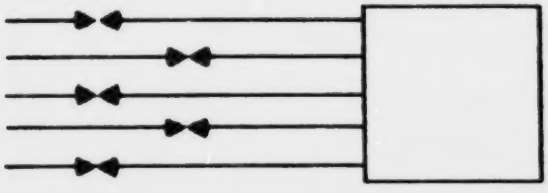


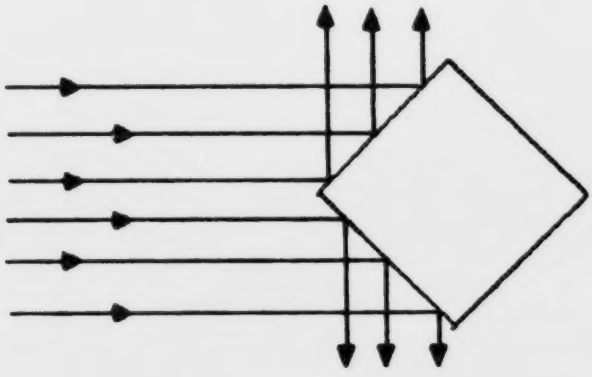
Figure 3.12/ Waveguides and Horns



A SMOOTH SPHERE SCATTERS ISOTROPICALLY

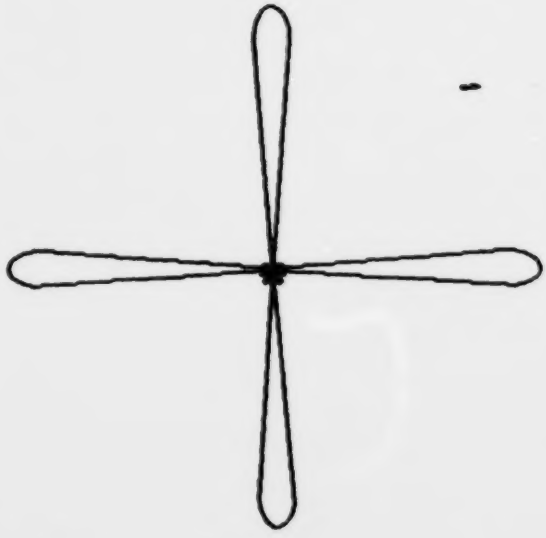


(a)



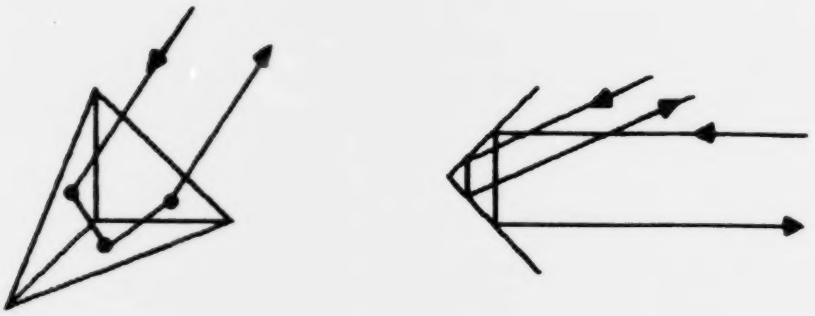
(b)

SCATTERING FROM A CUBE
DEPENDS ON ORIENTATION

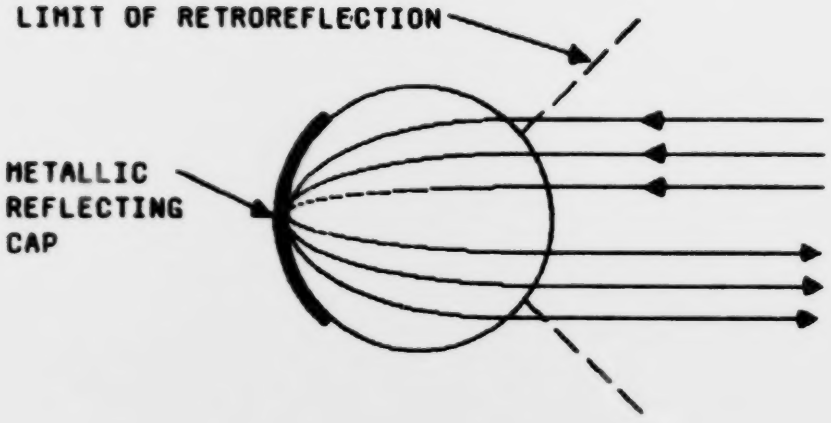


HORIZONTAL RADAR CROSS SECTION
PATTERN OF A LARGE CUBE
THE LARGER THE CUBE THE
NARROWER THE FOUR MAIN LOBES

Figure 3.13/ Radar Cross Section



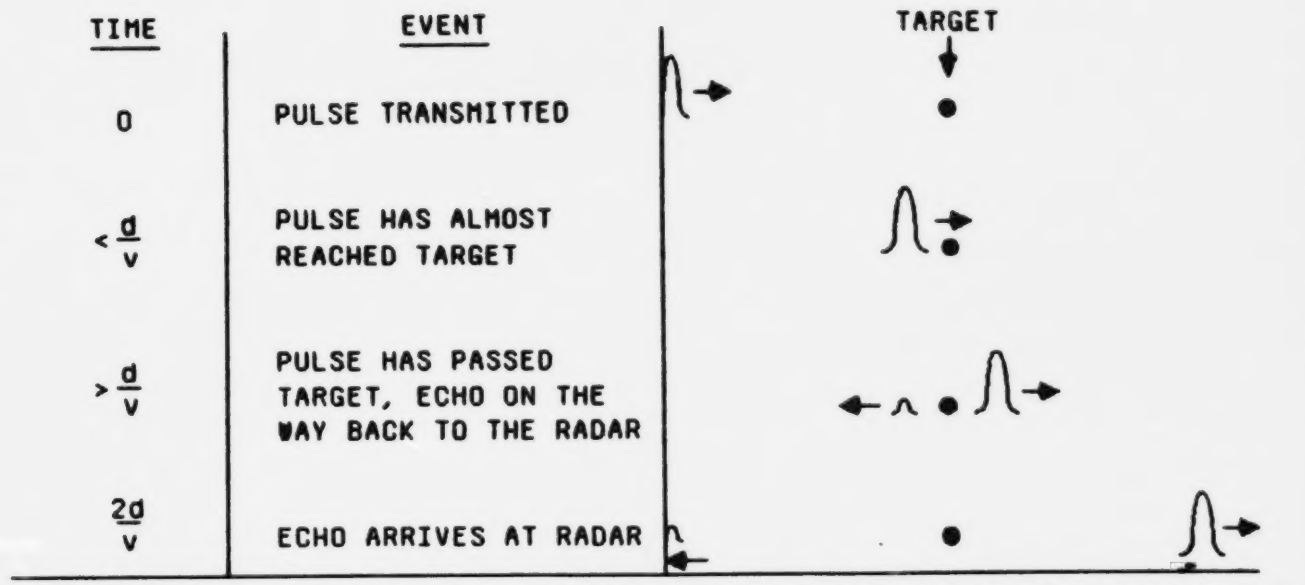
CORNER CUBE RETROREFLECTOR
(CORNER REFLECTOR)



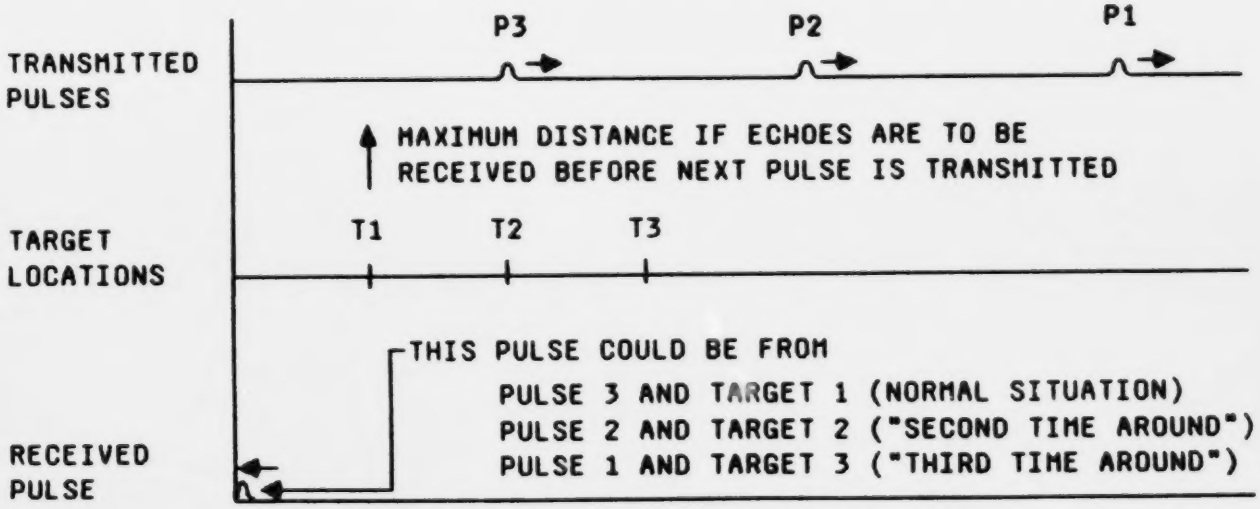
LUNEBERG LENS RETROREFLECTOR

(ABOVE DESIGN GIVES WIDE ANGLE RETROREFLECTION OVER THE SOLID ANGLE SUBTENDED BY THE METAL CAP. IF THE REFLECTING CAP IS REPLACED BY AN EQUATORIAL REFLECTING BAND OMNIDIRECTIONAL RETROREFLECTION IN THE PLANE OF THE BAND ONLY IS OBTAINED.)

Figure 3.14/ Radar Retroreflectors

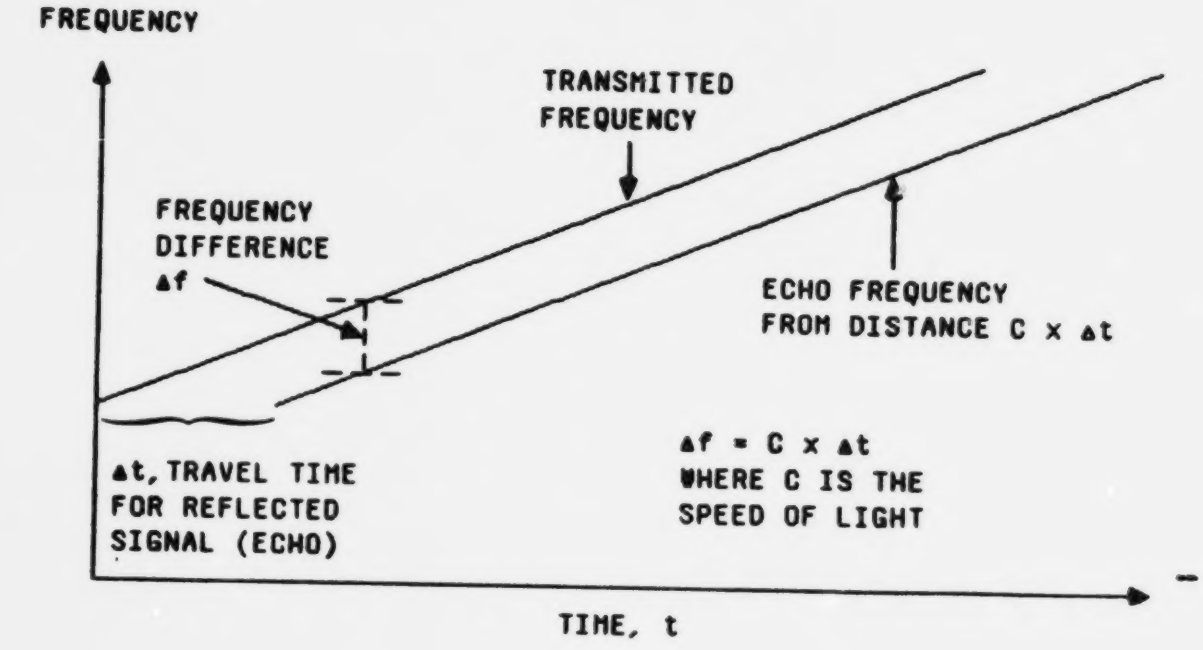


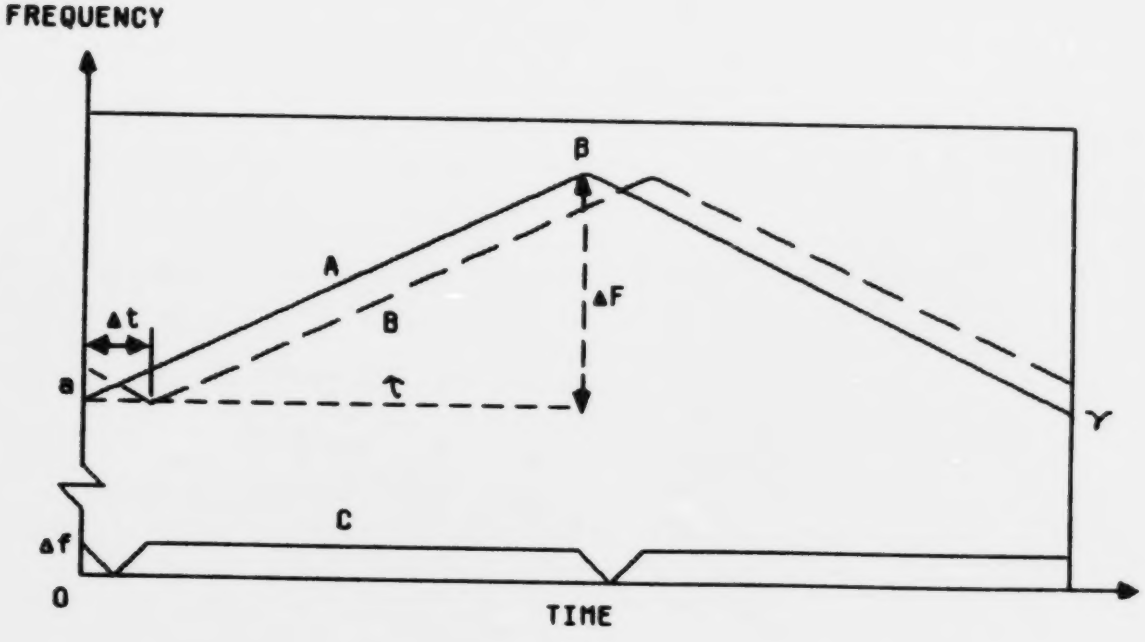
BASIC TIME-DISTANCE RELATIONSHIP IN RADAR



"SECOND TIME AROUND" ECHOES IN RADAR

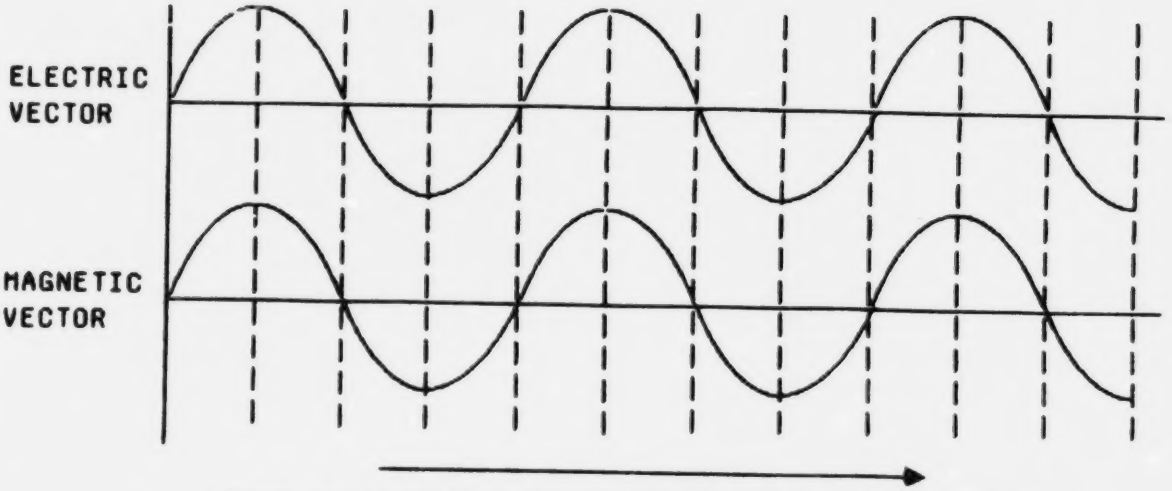
Figure 3.15/ Radar Range (Distance) Measurement


FREQUENCY
TRANSMITTED FREQUENCY
FREQUENCY DIFFERENCE Δf
ECHO FREQUENCY FROM DISTANCE C x Δt
Δf = C x Δt WHERE C IS THE SPEED OF LIGHT
Δt, TRAVEL TIME FOR REFLECTED SIGNAL (ECHO)
TIME, t

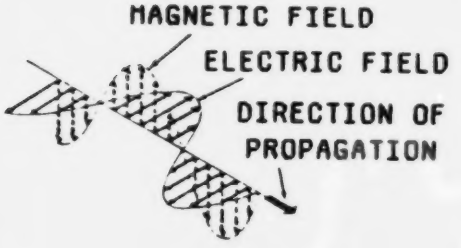


SCHEMATIC DIAGRAM FOR A TRIANGULARLY MODULATED FM

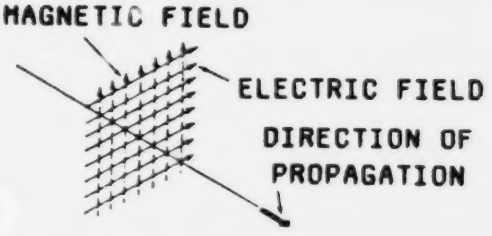
Figure 3.16/ Frequency Modulated Radar



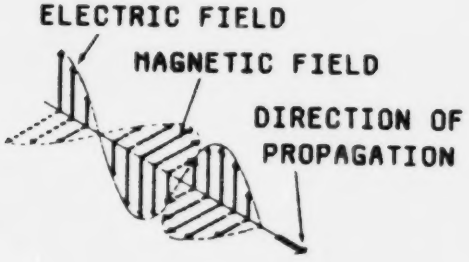
ELECTRIC AND MAGNETIC VECTORS ARE PERPENDICULAR TO EACH OTHER AND TO THE DIRECTION OF PROPAGATION.



(A) HORIZONTALLY POLARIZED WAVE



(B) A SMALL PART OF ONE WAVE FRONT OF FIG. A



(C) VERTICALLY POLARIZED WAVE

Figure 3.17/ Electromagnetic Waves

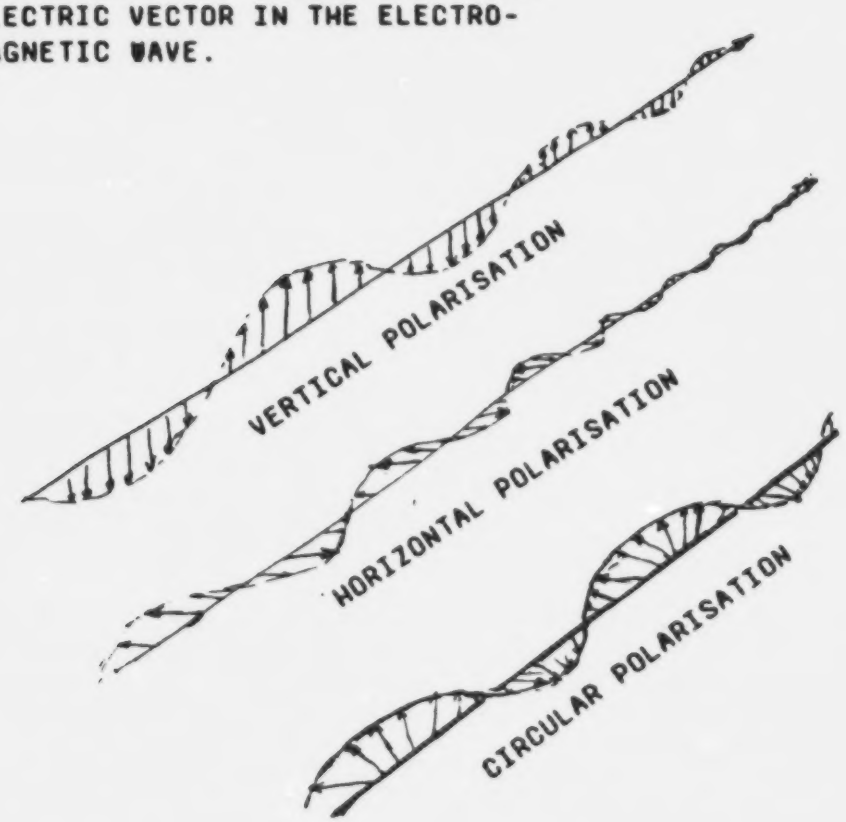
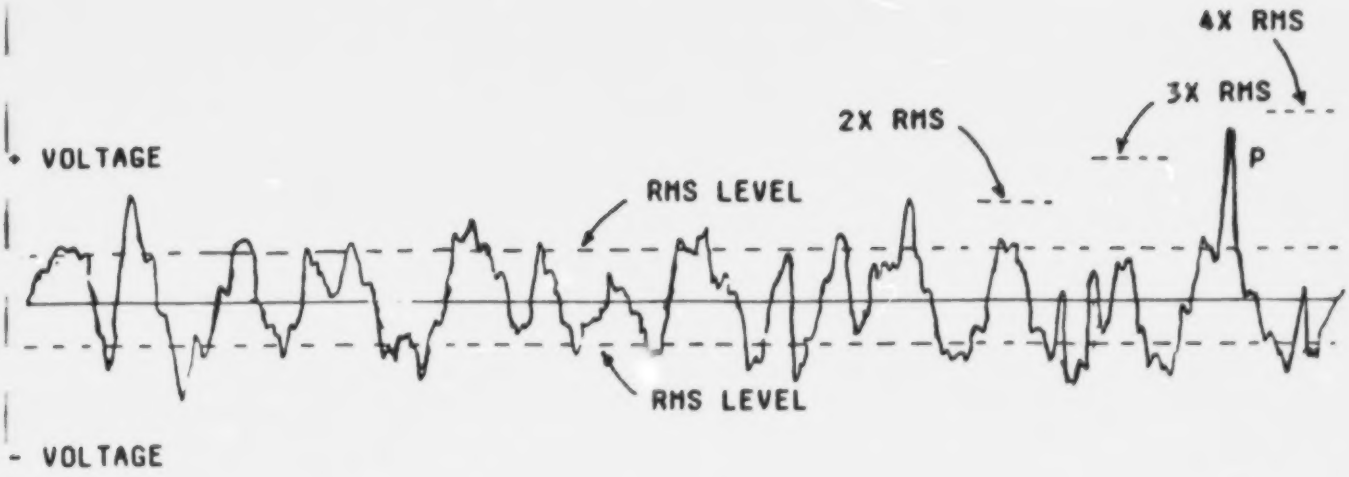

ARROWS SHOW THE DIRECTION OF THE ELECTRIC VECTOR IN THE ELECTRO-MAGNETIC WAVE.
VERTICAL POLARISATION
HORIZONTAL POLARISATION
CIRCULAR POLARISATION

Figure 3.18/ Polarization of Electromagnetic Waves



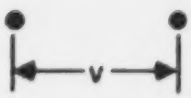
If the above is the output of a radar receiver, the pulse marked P might be either a very small echo or a noise peak. If the threshold were set at 3 times (9 dB above) the r.m.s. noise level, this pulse would be accepted as a true echo, although there would be a high probability it was only noise. If the threshold were set at 4 times (12 dB above) the r.m.s. noise level, the pulse would be ignored, i.e. treasted as noise. To avoid high rates of false alarm, the threshold must be set high enough to ignore some weak echoes.

Figure 3.19/ Effect of Noise on interpretation of the Receiver Output

CONSIDER TWO RECEIVERS, ONE STATIONARY AND ONE MOVING TOWARD TRANSMITTER.

AFTER 1 SECOND THE FIXED RECEIVER HAS RECEIVED "f" WAVEFRONTS, AND THEREFORE SEES A FREQUENCY "f"

AFTER 1 SECOND THE MOVING RECEIVER HAS RECEIVED MORE WAVEFRONTS



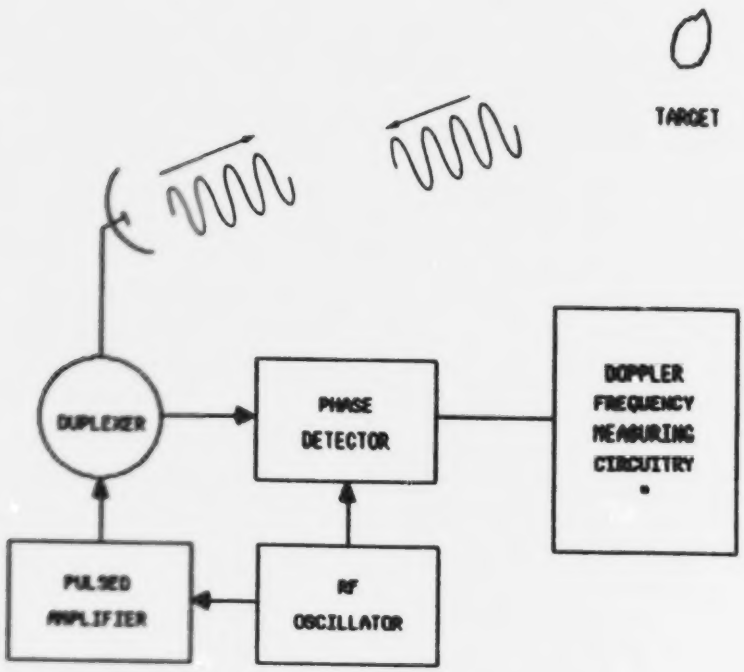
THAN THE FIXED RECEIVER BECAUSE IT IS MOVING TOWARD THE TRANSMITTER.

THE NUMBER IS $f(1+\frac{v}{c})$ AND THEREFORE THE MOVING RECEIVER SEES A FREQUENCY $f(1+\frac{v}{c})$ OR $f+\frac{fv}{c}$.

i.e. DOPPLER SHIFT = fx AMOUNT BY WHICH PATH SHORTENS PER SECOND

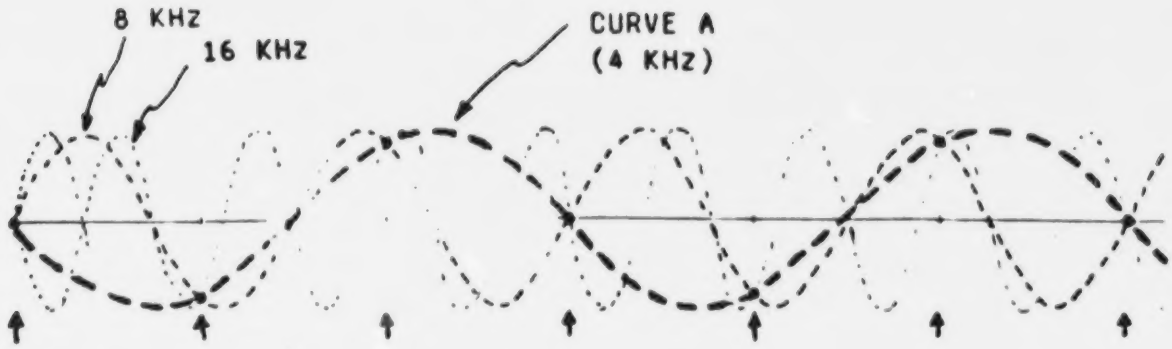
∴ FOR A TARGET MOVING TOWARD THE RADAR TRANSMITTER/RECEIVER AT VELOCITY v, DOPPLER SHIFT = $\frac{2vf}{c}$

Figure 3.20/ Doppler Frequency Shift



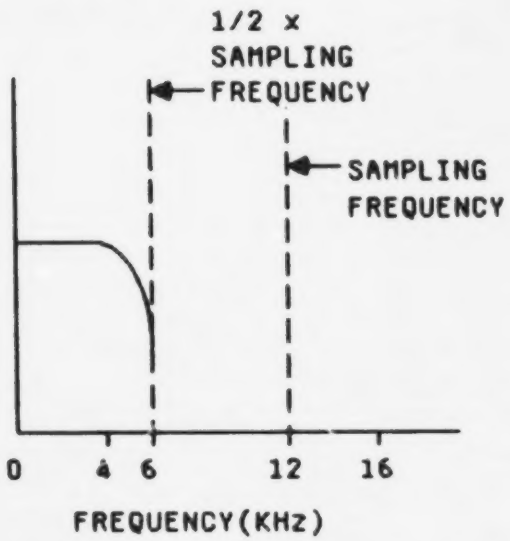
* THE DOPPLER FREQUENCY MEASURING CIRCUITRY MAY BE A BANK OF FILTERS, A SPECTRUM ANALYSER, A HARDWARE FOURIER TRANSFORM DEVICE, A COMPUTER, ETC.

Figure 3.21/ Measurement of Doppler Shift

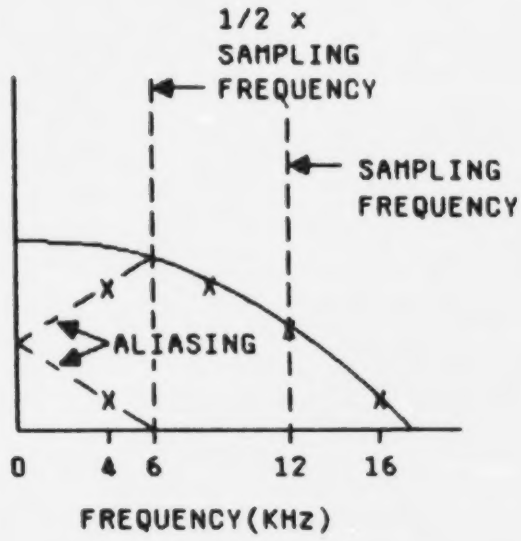


SAMPLING
POINTS
12 KHZ

IF THE WAVE FORM IS SAMPLED AT THE POINTS INDICATED (12 KHz), WE WOULD RECONSTRUCT THE WAVE AS SHOWN BY CURVE A. THIS WILL BE CORRECT IF NO FREQUENCIES HIGHER THAN 6 KHz ARE PRESENT, BUT IF FREQUENCIES OF 8 KHZ OR 16 KHZ ARE PRESENT, THEY CAN RESULT IN THE SAME SUCCESSION OF SAMPLES, AND SO BE FALSELY INTERPRETED AS SIGNALS AT 4 KHZ. THUS, IT IS IMPORTANT TO EXCLUDE FREQUENCIES ABOVE HALF THE SAMPLING FREQUENCY BY MEANS OF A FILTER TO AVOID ALIASING, I.E. FREQUENCY COMPONENTS " MASQUERADING " AS OTHER FREQUENCIES.

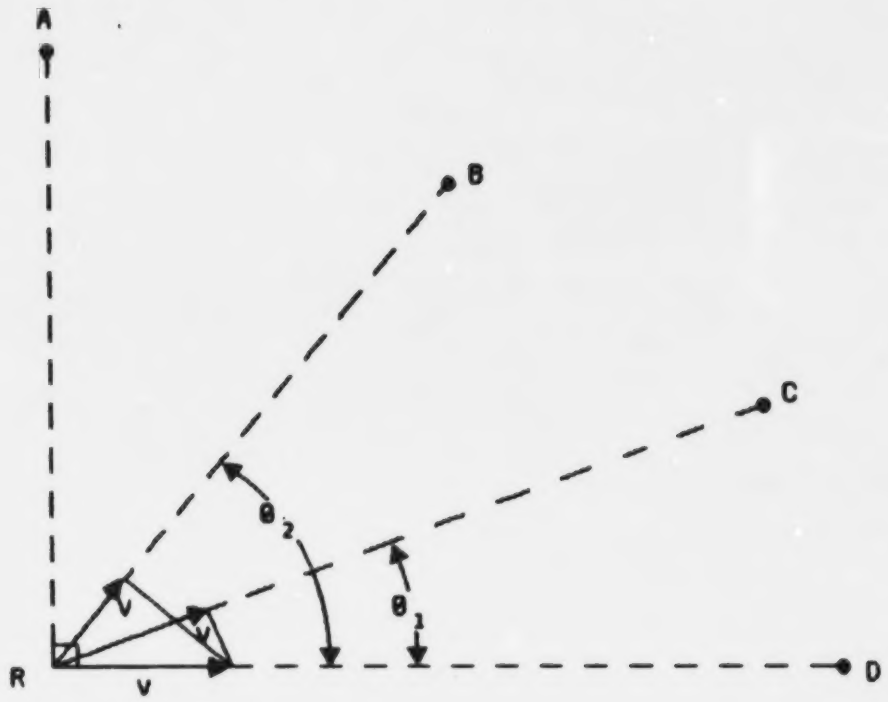


RIGHT! NO ALIASING.
(FREQUENCIES ABOVE 1/2 x
SAMPLING FREQUENCY REMOVED)



WRONG!

Figure 3.22/ Aliasing



- IF VELOCITY OF VEHICLE R IS v :

  COMPONENT OF VELOCITY TOWARD D IS V

  COMPONENT OF VELOCITY TOWARD C IS v COS θ_1

  COMPONENT OF VELOCITY TOWARD B IS v COS θ_2

  COMPONENT OF VELOCITY TOWARD A IS ZERO(v COS 90° = 0)

- IN EACH CASE DOPPLER FREQUENCY IS PROPORTIONAL TO THE VELOCITY COMPONENT.

Figure 3.23/ Doppler Frequencies from Targets Off the Vehicle Track

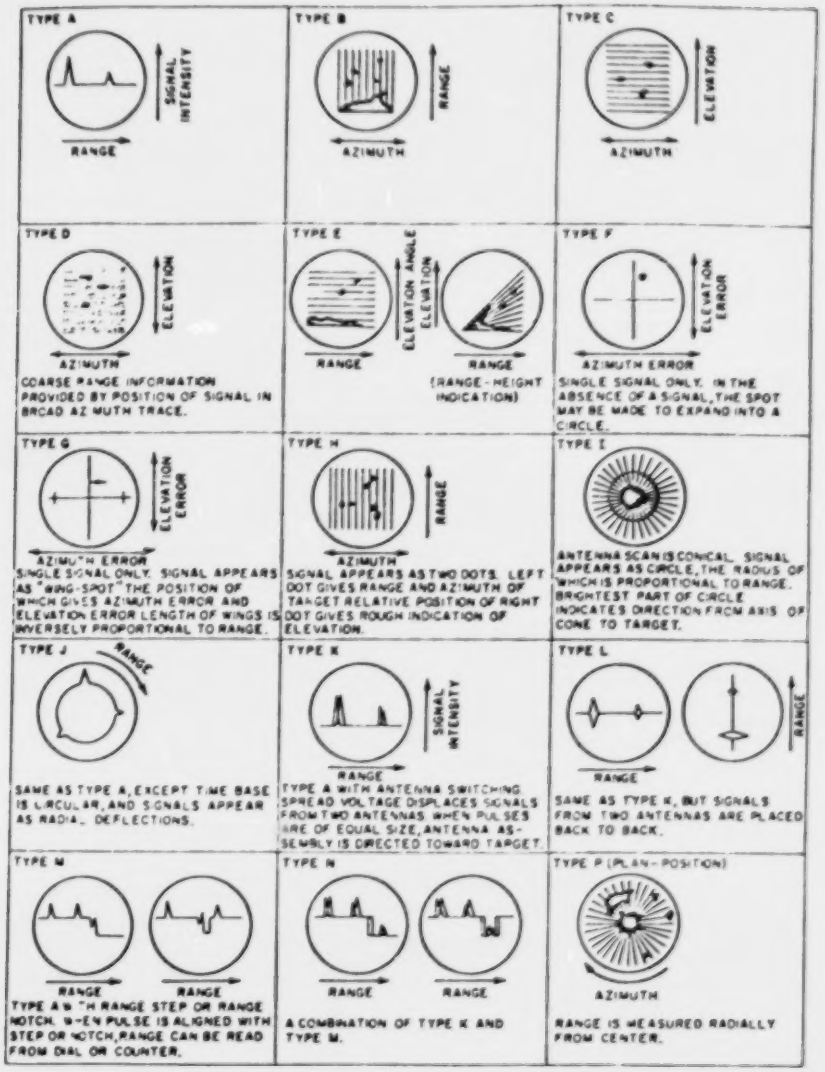
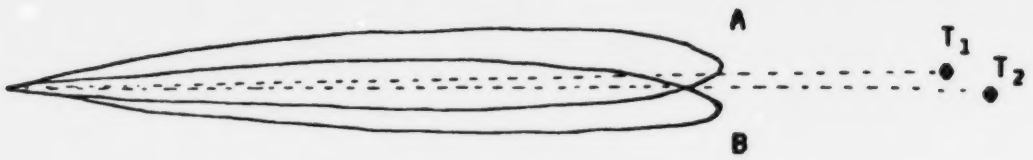
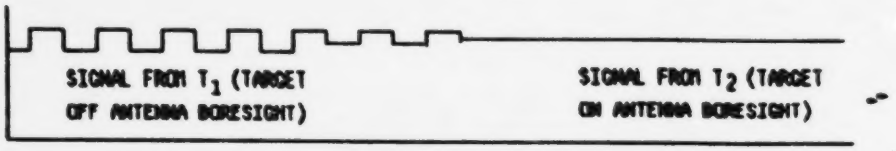

TYPE A
SIGNAL INTENSITY
RANGE
TYPE B
RANGE
AZIMUTH
TYPE C
ELEVATION
AZIMUTH
TYPE D
ELEVATION
AZIMUTH
COARSE RANGE INFORMATION PROVIDED BY POSITION OF SIGNAL IN BROAD AZIMUTH TRACE.
TYPE E
ELEVATION ANGLE
ELEVATION
RANGE
RANGE
(RANGE - HEIGHT INDICATION)
TYPE F
ELEVATION ERROR
AZIMUTH ERROR
SINGLE SIGNAL ONLY. IN THE ABSENCE OF A SIGNAL, THE SPOT MAY BE MADE TO EXPAND INTO A CIRCLE.
TYPE G
ELEVATION ERROR
AZIMUTH ERROR
SINGLE SIGNAL ONLY. SIGNAL APPEARS AS "WING-SPOT" THE POSITION OF WHICH GIVES AZIMUTH ERROR AND ELEVATION ERROR LENGTH OF WINGS IS INVERSELY PROPORTIONAL TO RANGE.
TYPE H
RANGE
AZIMUTH
SIGNAL APPEARS AS TWO DOTS. LEFT DOT GIVES RANGE AND AZIMUTH OF TARGET RELATIVE POSITION OF RIGHT DOT GIVES ROUGH INDICATION OF ELEVATION.
TYPE I
ANTENNA SCAN IS CONICAL. SIGNAL APPEARS AS CIRCLE, THE RADIUS OF WHICH IS PROPORTIONAL TO RANGE. BRIGHTEST PART OF CIRCLE INDICATES DIRECTION FROM AXIS OF CONE TO TARGET.
TYPE J
RANGE
SAME AS TYPE A, EXCEPT TIME BASE IS CIRCULAR, AND SIGNALS APPEAR AS RADIAL DEFLECTIONS.
TYPE K
SIGNAL INTENSITY
RANGE
TYPE A WITH ANTENNA SWITCHING. SPREAD VOLTAGE DISPLACES SIGNALS FROM TWO ANTENNAS WHEN PULSES ARE OF EQUAL SIZE, ANTENNA ASSEMBLY IS DIRECTED TOWARD TARGET.
TYPE L
RANGE
SAME AS TYPE K, BUT SIGNALS FROM TWO ANTENNAS ARE PLACED BACK TO BACK.
TYPE M
RANGE
RANGE
TYPE A WITH RANGE STEP OR RANGE NOTCH. 9-Eγ PULSE IS ALIGNED WITH STEP OR NOTCH, RANGE CAN BE READ FROM DIAL OR COUNTER.
TYPE N
RANGE
RANGE
A COMBINATION OF TYPE K AND TYPE M.
TYPE P (PLAN-POSITION)
AZIMUTH
RANGE IS MEASURED RADIALLY FROM CENTER.

Figure 3.24/ Radar Display Types

Types A, B, E and P are of interest to us.



- SWITCHED BEAM TRACKING. PATTERNS A AND B ARE GENERATED SEQUENTIALLY BY SWITCHING FROM ONE ANTENNA FEED TO ANOTHER AT FREQUENCY f_s.



ERROR SIGNAL AT f_s IS ZERO WHEN ANTENNA POINTS TOWARD TARGET AND CHANGES PHASE AS THE TARGET MOVES TO THE OTHER SIDE.

- MONOPULSE TRACKING. THE TWO BEAMS ARE GENERATED SIMULTANEOUSLY AND THE TWO RECEIVED SIGNALS SEPARATED IN CIRCUITRY. THE

$\frac{A-B}{A+B}$. THIS CHANGES SIGN AS THE TARGET CROSSES THE CENTER LINE.

FOR T_1 $\frac{A-B}{A+B}$ IS POSITVE. FOR T_2 $\frac{A-B}{A+B}$ IS ZERO.

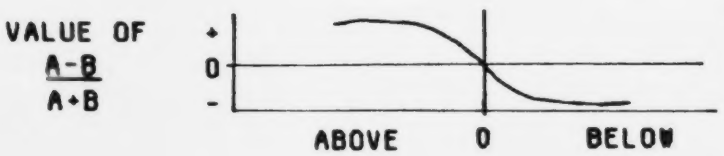


Figure 3.25/ Radar Tracking Techniques

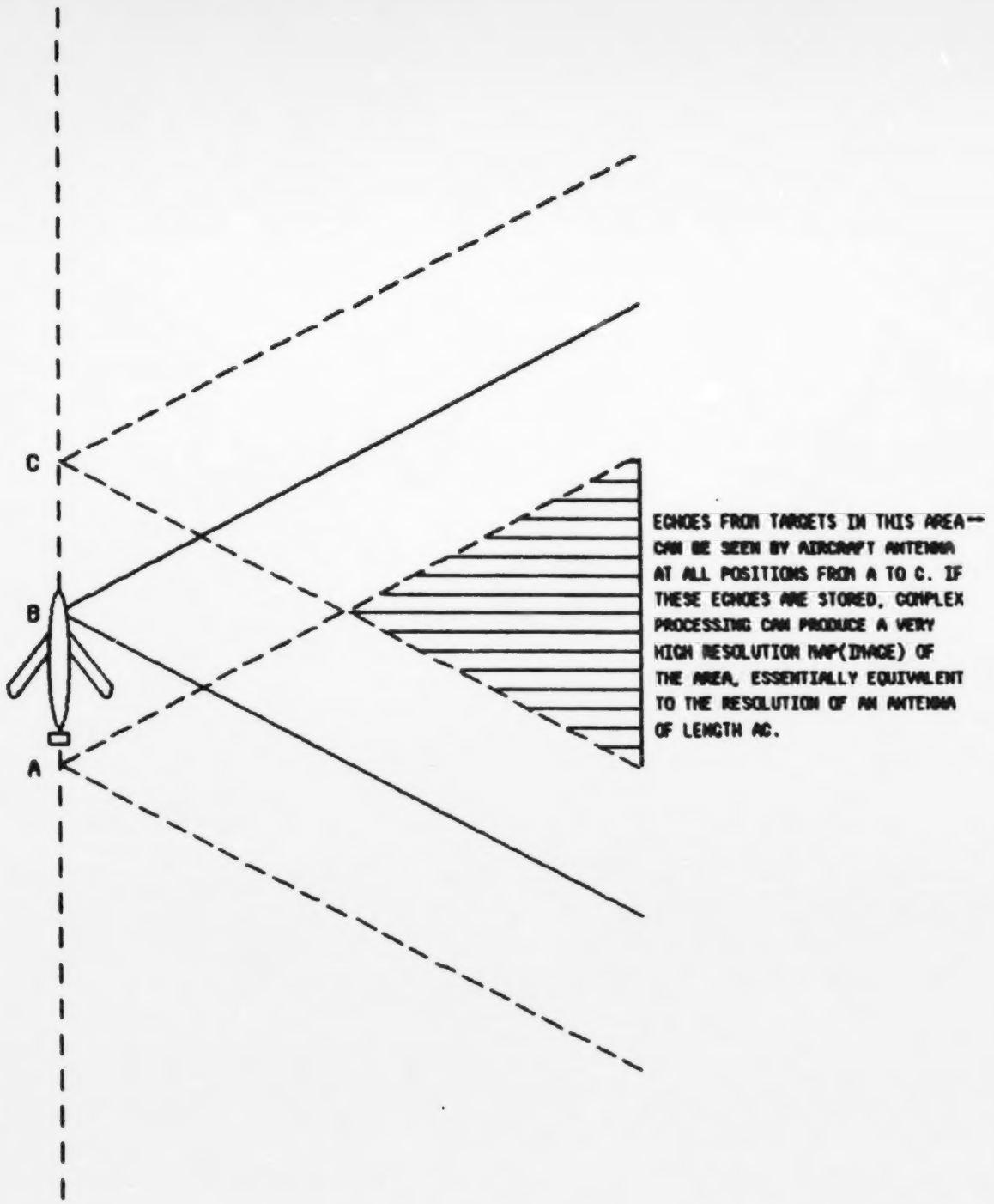
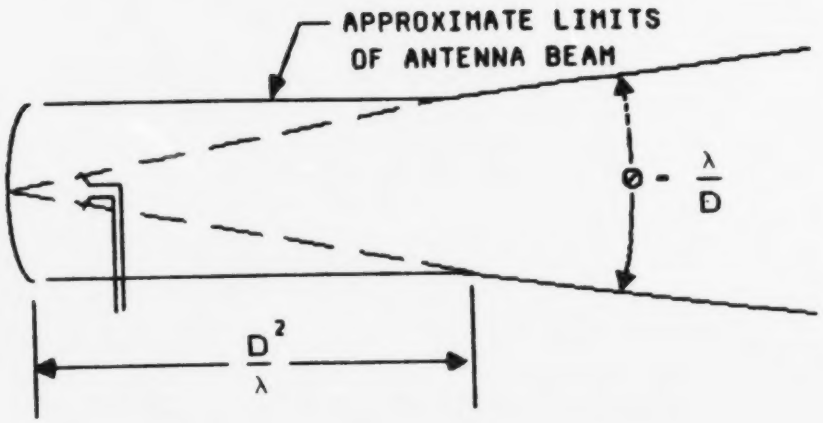

C
B
A
ECHOES FROM TARGETS IN THIS AREA CAN BE SEEN BY AIRCRAFT ANTENNA AT ALL POSITIONS FROM A TO C. IF THESE ECHOES ARE STORED, COMPLEX PROCESSING CAN PRODUCE A VERY HIGH RESOLUTION MAP(IMAGE) OF THE AREA, ESSENTIALLY EQUIVALENT TO THE RESOLUTION OF AN ANTENNA OF LENGTH AC.

Figure 3.26/ Synthetic Aperture Principle and Side-Looking Radar



D = DIAMETER OF ANTENNA

λ = WAVELENGTH

Figure 3.27/ Antenna Beam Size

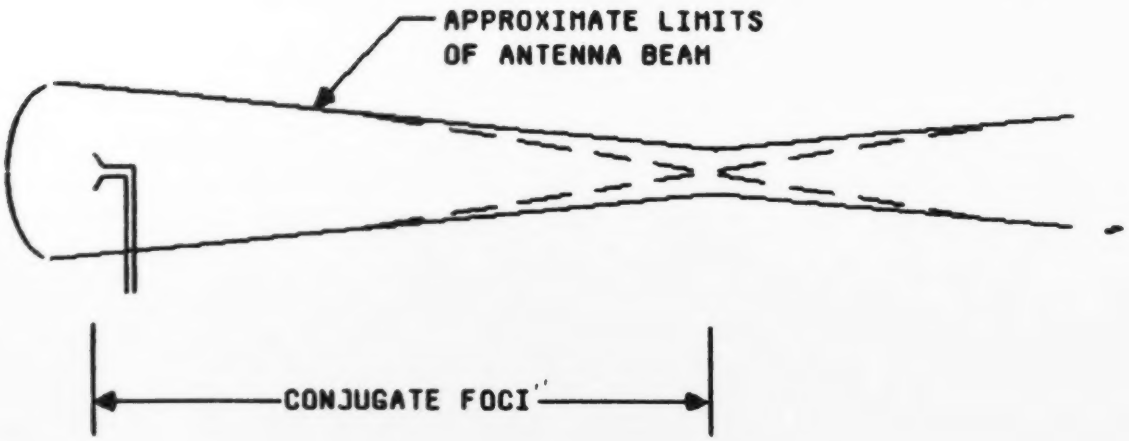
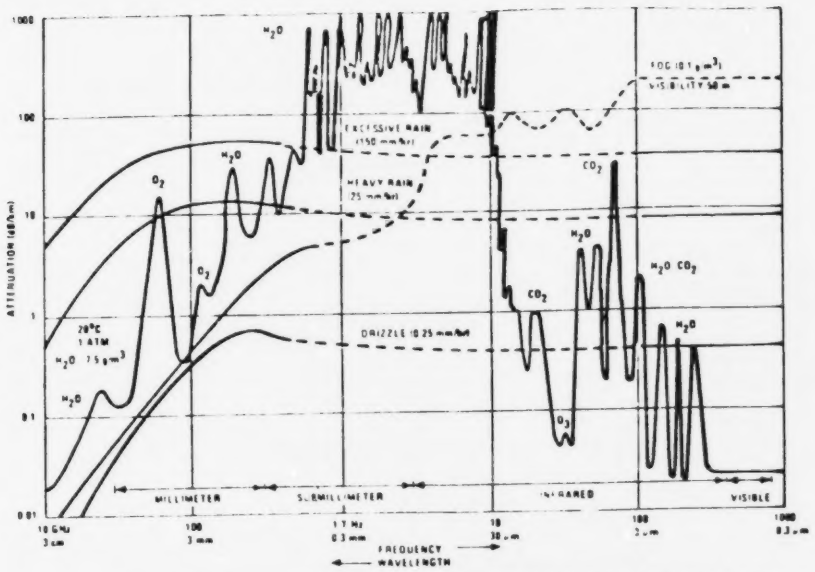
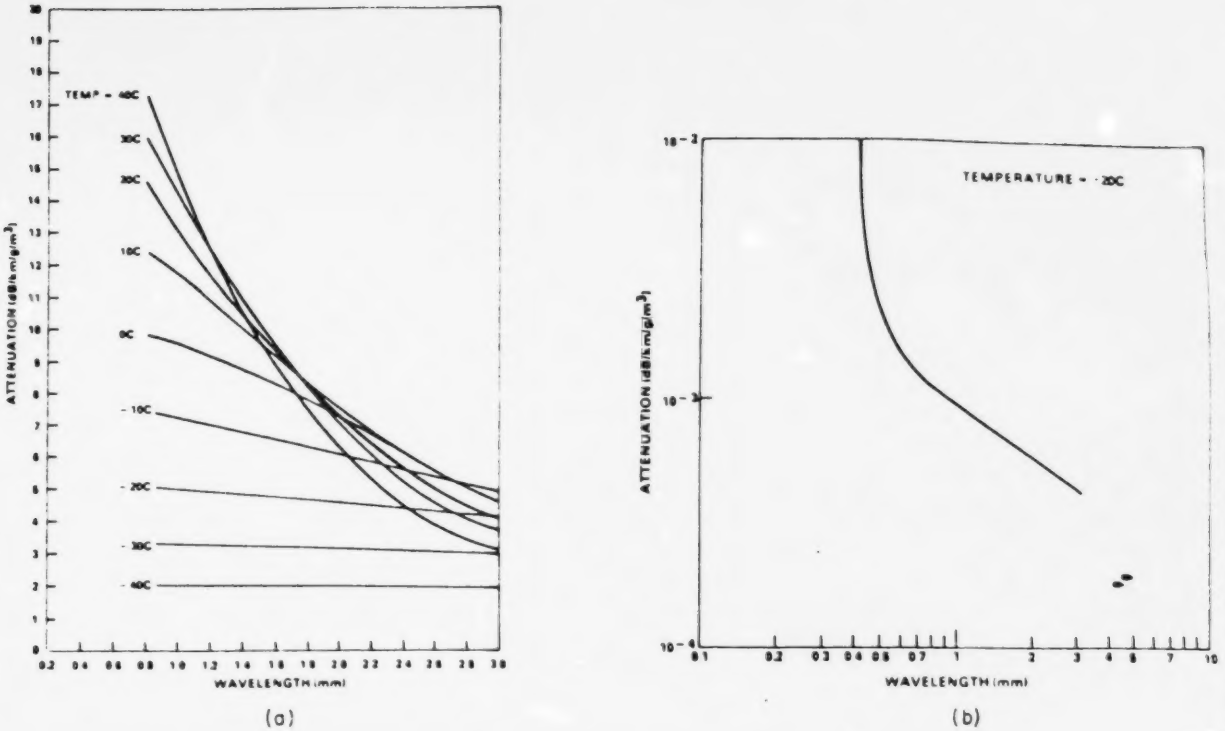


Figure 3.28/ Focused Antenna



Atmospheric attenuation characteristics for wavelengths 3 cm to 0.3 μm.

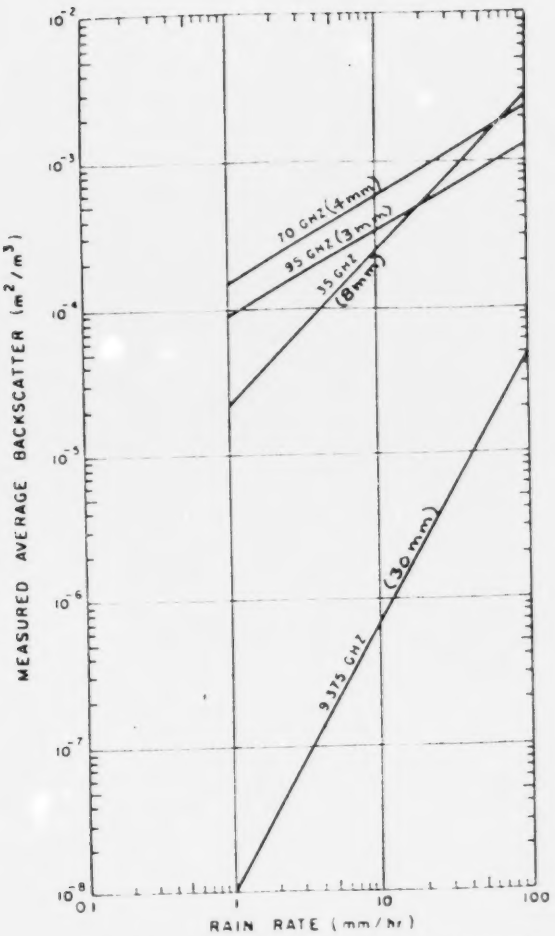
Figure 3.29/ Clear Weather Atmospheric Attenuation



Fog and cloud attenuation properties. (a) Cloud and fog attenuation, (b) ice cloud or fog attenuation.

Figure 3.30/ Fog Attenuation

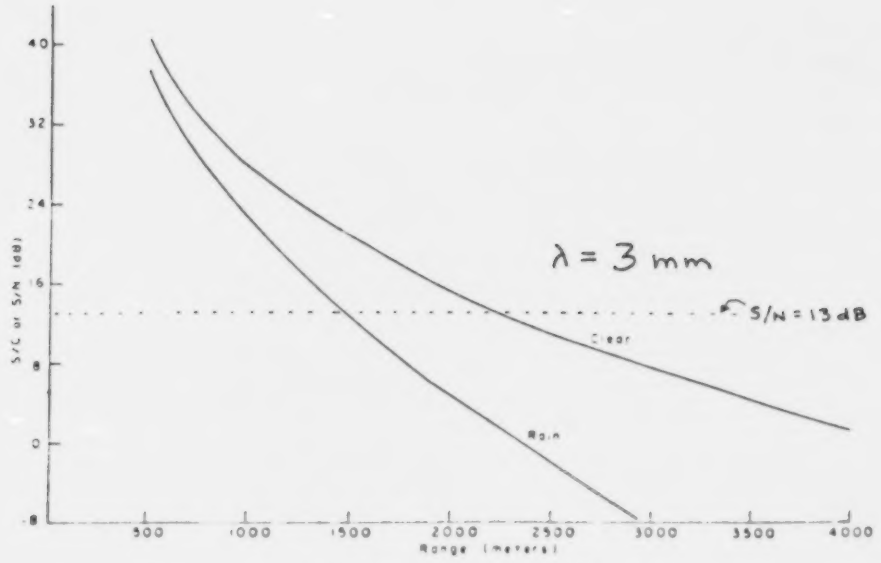
Multiply Attenuation by Fog Density (GM/M^3 of H_2O)



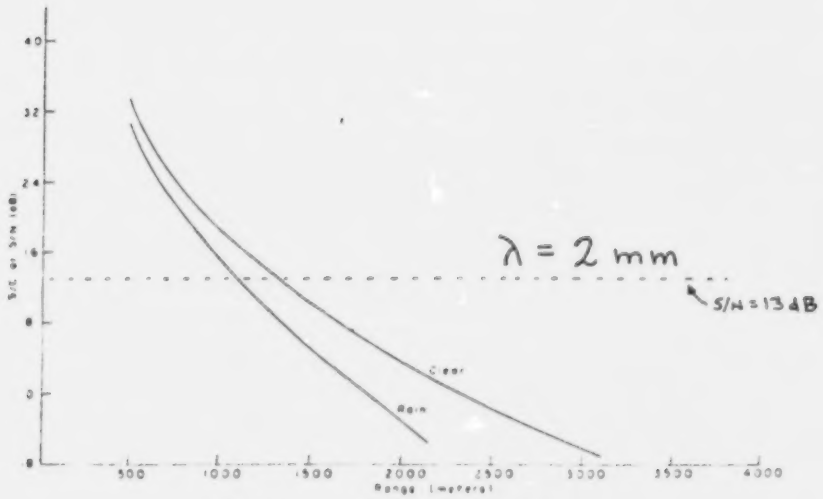
Rain reflectivity coefficient versus rain rate, vertical polarization

Figure 3.31/ Radar Cross Section of Rain Per Unit Volume

Multiply Cross Section by Volume of Radar Resolution Cell.



Performance curves for the 94-GHz radar.



Performance curves for the 140-GHz radar.

Figure 3.32/ Calculated Radar Performance in Rain

(Adapted from Ref. 11)

4/ INTRODUCTION - LASERS

For active vision systems based on lasers one should look at the various schemes presently available and the salient features discussed. A number of useful articles have been identified and are listed for background reading [1 - 9]. The most obvious method is the laser radar rangefinder (based on time of flight measurements) and most of the following discussion will be based on this method. For completeness the other methods which may be used for active vision sensors will be briefly described. One of these methods is laser holography.

The various parameters involved with a laser radar rangefinder are specified depending on the types of measurements which are to be measured: e.g. velocity or range of an object. Other factors of obvious importance are what accuracies, what types of images and what resolutions are required. Similar methods which are used for laser rangefinders may also be applied to imaging systems and robotics but the latter still appear to be in an experimental stage.

The laser rangefinder design is fundamentally based on the time of flight to and from an object or target and the range of this object is the factor which is to be determined. As a summary one should review the various systems used to perform different measurements. Various types of lasers enable various types of measurements to be made[8]:-

a) cw (Continuous Wave)

The cw laser allows very accurate velocity measurements to be made but it cannot be used to measure range (see b). The principle is as follows: when the laser beam bounces off an object it is Doppler shifted by any motion in that object. On the return, the signal is detected and

mixed with another beam for coherent detection (see section 4.4). As a result of the fact that the frequency shift is dependent on the object velocity it is a relatively easy task to identify the velocity. Stationary background clutter which could also obscure a moving target can also be minimized by filtering out zero velocity contributions.

The Doppler shifted frequency is given by equation (4.1)

$$F_D = \frac{2 \times V_r \times F_t}{c} \qquad (4.1)$$

where F_t = transmitted frequency

c = velocity of propagation

V_r = relative velocity of target with respect to radar.

Table 4.1 shows the Doppler shift for various relative speeds at different transmitted frequencies. To obtain an unambiguous signal (for both cw and pulse radar) the rate of modulation must be greater than two times the expected Doppler shift. The advantage of laser radar over millimetre systems is that (from equation 4.1) the magnitude of the Doppler shift increases with transmitted frequency. This advantage becomes significant in the case of slow moving objects, where the observed frequency shift will be larger for laser type systems, and which in turn makes signal processing easier.

b) If relative ranging is required an amplitude modulation can be applied to the cw laser beam prior to transmission. In this situation the phases of the transmitted and reflected beams are compared and it is found that the phase shift varies with the distance to the target (over a small range of distances)[8].

c) A cw method of measuring both range and velocity is possible but the information is intertwined. This technique is known as FM pulse compression.

d) Pulsed techniques can be utilized and this is in fact the simplest and most common technique used for ranging. They however provide only limited velocity information. In this situation a pulse is transmitted and the round trip time to the target is recorded. It has been reported that range accuracies of a few metres can be achieved with relatively simple circuitry but improved accuracies can be achieved with more sophisticated circuitry. One commercial rangefinder is quoted as giving ranges of up to 11.5 km ± 2 m accuracy[10].

Factors affecting the choice of operating systems would be: reflectivity of targets, scattering and atmospheric effects, background effects, intensity of illuminating source etc. Other factors are related to what type of information is required. If only knowledge about the presence of an object is required a relatively simple system would be utilized. If however identification of the object is required, a much more elaborate diagnostic system would be used and present work indicates long processing times (for stationary objects)[11]. The specific details will not be presented within this brief review, but a summary of the current work being undertaken will be given.

Another important consideration which must be treated is whether indoor or outdoor environments are to be encountered. In Section 4.5 the role of atmospheric effects will be discussed and it will become evident that different laser systems would be more suitable for the different environments.

The applications of laser systems will be treated briefly in Section 4.8 to give the reader some idea of what may be possible (and also what limitations are associated with such systems).

4.1/ Range Equation and Discussion

Fundamental to the description of a laser radar rangefinder is the range equation which relates the receiver power to the transmitted power and this is given in equation (4.2) [5, 10, 12].

$$P_r = P_t\left(\frac{1}{R^2\,\Omega_T}\right)\left(\frac{A_s}{R^2\Omega_s}\right) A_r\, T^2 loss\, \sigma_s \qquad (4.2)$$

From this we see that it is based on the classical microwave radar equation except that in the optical region the beamwidth rather than the antenna gain is the measured quantity. The terms of the equation are given by:

P_r, P_t = received and transmitted powers

R = range from the transmitter to target

Ω_t = solid angle of the diverging transmitted beam

Ω_s = solid angle of the beam scattered or reflected by the target

A_s = target cross section

A_r = effective aperture of the detector

Tloss = one way transmission loss

σ_s = scattering coefficient or target reflectivity

It is obvious that increasing the transmitted power will result in an increase in the final received power, thus it may be beneficial to use the highest power available, providing some other important criteria are satisfied (cost, safety, size etc.). These factors will be discussed briefly.

The equation expresses the fact that only energy in a solid angle A_s/R^2 of a transmitted beam of solid angle Ω_t is reflected (or scattered). The reflected (or scattered) energy is confined to a solid angle Ω_s, but only that fraction within the solid angle A_r/R^2 will be collected.

It is evident therefore that a small amount of energy is going to be detected and this puts a number of constraints on the chosen system.

Some of the terms of the equation will now be discussed:

σ_s: The scattering coefficient is a function of great importance in determining the amount of energy which will be seen by the receiver. σ_s is given by the ratio between the scattered and incident energy and depends on wavelength, and target material and surface. Measurements would have to be performed to ascertain the particular σ_s values for objects which may be encountered. Some workers have quoted values of 10% for this parameter[12, 13].

Ω_t: Collimation of transmitting beam

One advantage of the laser over conventional sources is the ability to achieve beams with extremely low divergence (mRads) and this feature makes the laser an effective source for target illumination. In addition, to be able to illuminate with a well collimated beam ensures optimum use of the available power.

In Table 4.2 we show the various beam divergence values (minimum) for various wavelengths and conditions. A 10 cm aperture was chosen for convenience since this is a readily available aperture size [8].

The actual divergence and resolutions available are calculated from the various parameters and characteristics of the chosen laser. Each will have its own divergence and beam properties which will dictate the

external optics required to collimate the laser beam. Once this information is known exact figures could be derived. Typical however, and easily achievable, are beam divergences of the order of a few milliradians for visible or IR lasers, thus making them effective illumination sources.

Ω_s: Divergence of Scattered Energy

The divergence of the scattered energy is important when considering the detector efficiency. In this case one must consider that the radiation is backscattered into a solid angle of 2π. In addition, it is not possible without detailed information on the reflectivity vs. incident and reflected angles to make effective estimates and for this reason we use the above assumption.

A_s: Target Cross Section

The energy backscattered depends on the target scattering cross section. If a laser is used as a source the target cross section area can be greater than the cross section of the incident beam giving: $A_s = R^2 \times \Omega_t$ (where A_s is the actual area). The range equation is then simplified and the backscattered power P_r will decrease more slowly and will be $\alpha\ R^{-2}$ rather that R^{-4} (5, 12).

A_r: Receiver Aperture

The receiver aperture in IR and visible sensors can be described as the radiation collecting area of the detector of the receiving telescope. Apertures of 10 - 20 cm are common.

P_t: Power of Source

The power of the source can vary over many orders of magnitude depending on the particular source used. In reference (14) the powers for various laser sources available are listed. The most promising source

is possibly the mini TEA CO_2 laser (due to size/power) with 250 kW (1J/pulse) being available. For more details and description of the Radar Range Equation the Reader is referrred to Section 3.3.3 of this report.

4.2/ Receiver Sensitivity

To analyze the receiver sensitivity one must estimate the total power, not only from the target but also from all other sources. After an estimate of the resulting signal to noise ratio is made, the feasibility of individual systems would be possible. In this section the effects of molecule or particle backscatter in the atmosphere will be described briefly.

The receiver sensitivity can be studied by evaluating the signal to noise (S/N) where S is the signal power returned from the target and N the total noise power for all sources. One controllable noise figure is that of the detector. Various types of detector are available and the choice is dependent not only on the S/N, but also the wavelength ranges being used. Another technique is what form the detection will take (Direct or Coherent) and this is described in Section 4.4.

4.3.1/ Background noise

Background noise can be described in part by the background spectral radiance and some data has been published on this subject and values are presented in Table 4.3. The values are dependent on the atmospheric conditions and wavelength.

The noise due to the background emission is given by equation (4.3)

$$P_b = N_b(\lambda)\Delta\lambda\Omega_r A_r \qquad (4.3)$$

where $\Delta\lambda$ is the filter spectral bandwidth

Ω_r is the receiver field of view (solid angle)

A_r is the receiver detector surface area.

N_b is background spectral radiance

It is evident that contributions due to this background noise may result in poor performance of any system. The greatest source of noise results from the sky background and its effects can only be ascertained if the spectral radiance is known. Figure 4.1 shows the spectral radiance of the sky under clear daytime conditions [14].

4.3.2/ Backscatter

Another contribution of noise to the receiver results from backscatter of radiation from the source due to molecules and particles. The noise due to backscatter can be reduced considerably by a technique known as range gating [5]. This is a technique where the transmitted radiation is pulsed for short time periods and the receiver is turned on for an appropriate duration at a specific time delay corresponding to the required range. Obviously prior knowledge must be used to ascertain the gating period. For observation of a fixed scene this would be a relatively straightforward procedure however. The advantage of the gating technique is seen in the ability for the system only to view backscatter from molecules or particles near the target range and the backscattering from «objects» in the transmitting and returning radiation paths are eliminated.

4.4/ Detection

Another important decision in a laser ranging system is what type of detection system should be used. There are presently two commonly used techniques given by:

a) Direct Detection and

b) Coherent Detection

and both shall now be discussed.

a) In this case, which is the simplest form of detection available the only information which can be extracted is that of range. The principle can be described: - A pulse is transmitted to a target and the reflected radiation is brought onto a detector. With this system a relatively straightforward optical system is required.

b) The second form is coherent detection. This technique can be demanding on the overall system since the transmitted beam (of a known frequency) is reflected from a target and then mixed with a stable reference beam to provide a beat frequency. This frequency gives the difference between the reference and signal frequencies.

Two forms of coherent detection are possible: -

a) Homodyne

b) Heterodyne

Homodyne uses a portion of the signal beam, split off before transmission to use as a reference. This has two problems associated with it however and these are: -

It has problems sensing slow motion and cannot distinguish between forward and backward motion.

Heterodyne detection can perform both of these functions but a second laser source is required. This is known as the local oscillator and provides the reference beam. Obviously for meaningful measurements, a stable local oscillator must be used and this can be a limitation in the visible region but it is a reasonable proposition at IR and FIR wavelengths.

The choice of technique will depend directly on the types of measurements being made. Briefly:

For velocity measurements heterodyne is required, and for ranging, although direct detection is possible, the heterodyne technique is much more sensitive which is important if small signal levels are being encountered. For imaging, detector arrays may also be required. The subject of detectors will be discussed later.

4.5/ Atmospheric Effects

The atmospheric transmission of radiation is limited by two mechanisms namely, (1) elastic scattering loss due to Rayleigh and Mie scattering and (2) absorption. These effects will severely restrict any systems' performance if not considered since the transmission loss limits the range of the system. A number of articles have treated these effects and are referenced [15 - 24].

Elastic scattering is classified as Rayleigh or Mie scattering depending on whether the particle size is much smaller or comparable to the wavelength. Mie scattering is less wavelength dependent than Rayleigh scattering[15] and is usually much larger than Rayleigh in the visible and infrared regions. The Mie scattering depends on and varies with varying atmospheric conditions.

An empirical relation relating the Mie scattering coefficient to the visual range is often used and is given by [15]:

$$a_\lambda^{Mie} = \frac{3.91}{V}\left[\frac{0.55}{\lambda}\right]^{0.585} V^{1/3} \quad km^{-1} \qquad (4.4)$$

λ = wavelength

V = visual range.

Table 4.4 shows the scattering coefficients for various wavelengths[15].

In the infrared the atmosphere has several absorption bands due to water vapour and CO_2 absorption which limits the useful spectral regions to the so called atmospheric windows. Fig. 4.2 shows the atmospheric bands. Within the atmospheric windows the absorption loss over a 1 km path is significant and exceeds the scattering loss in medium clear day conditions. As an example, for visibility of 5 km, RH of 75%, and a temp. of 60°F (16°C), the absorption coefficients in the two IR windows, 2.7 to 4.3 μm and 4.3 to 6 μm are 0.4 and 0.8 km^{-1} respectively[17]. The corresponding Mie scattering coefficients are only 0.14 and 0.08 km^{-1}.

What should also be considered is that the object being observed by a sensor is scattering the received radiation into a solid angle of 2π, whilst the receiving optics only subtends a small solid angle at the target and this suggests a high power system is required (1 - 1000 W)[16].

From these considerations a few conclusions can be summarized as[16].

1) Laser wavelengths should occur in an atmospherically transparent region[15] to enable long paths to be used with small atmospheric attenuation.

2) For range resolved applications laser pulse lengths less than 500 ns are usually required. (Also from the reference there were

some practical limitations which should be described (relating to laser systems)).

3) The telescope and receiving system will be influenced by incoherent background radiation e.g. sun, earth or the atmosphere itself (i.e. these forms of radiation will be detected). This will produce a noise level which will then determine the lowest detectable backscattered signal.

These factors may be improved by:

a) choosing high transmission, narrow bandwidth optical filters around the laser wavelengths.

b) restricting the telescope field of view to encompass only the backscattered radiation from the source.

c) using coherent heterodyne detection[18]: this however requires th use of a second laser system.

From reference (19) we have that in the earths' atmosphere, rain, fog, smoke and haze are always present. Transmission losses have been estimated at[20]:

3 - 8 db/km for rain

3 - 10 db/km for fog

3 - 20 db/km for snow

Fig. 4.3 shows graphically the effects of rain and fog[21]. The quoted losses due to Fog have been found to be widely varying in the cited works (possibly due to the definitions used to describe the Fog conditions) and great care must be taken when deciding what performance would be expected in the final system.

Clearly most of these atmospheric effects change the amplitude of the transmitted beam rather than its frequency and so frequency modulated systems should be used in preference to AM modulated systems.

From reference [22] the optical transmission of energy is ususally expressed by Equation 4.5.

$$T = \exp(-\sigma R) \qquad (4.$$

where σ is the attenuation coefficient (or extinction coefficient) and R is the length of the transmission path. This reference also gives a very extensive review of transmssion curves for varying conditions.

It is apparent that these atmospheric effects will not be so important in the indoor environment and any system so used would be operated in a reasonably controlled environment and would make the choice of system a relatively easy task.

4.6/ Safety

One important consideration in such vision sensors would be the amount of radiation which would be seen by the human eye. For guidelines we use the Laser Institute of America Laser Safety Guide[25].

Most retinal damage effects are possible when laser emission lies within the wavelength range 0.4 to 1.4 μm which covers the visible and the Nd Yag lasers. These lasers are also possible candidates for such vision sensor sources. The obvious eye safe laser is the CO_2 laser (10.6 μm) and this is one reason why the CO_2 laser now finds extensive applications in rangefinders (stemming from military applications).

Laser radiation which enters the eye directly will be focussed to an extremely small image, with large power densities, onto the retina and cause permanent damage (for the first wavelength range region described). Tables 4.5(a) and 4.5(b) show the current safety limits for various laser wavelengths.

As a precaution the transmission should always be adjusted so that after atmospheric attenuation the received power by the target is below the maximum permissible level. The calculation of received power in

an active sensor would be difficult in an automatic system since a sophisticated system would be required to ensure at all times the laser power is within safe limits. One way to do this would be to constantly adjust the power such that safety levels are retained. This problem is reasonably controllable in indoor environments since the overall transmission levels should remain constant. Outdoor environments which are uncontrollable present more serious difficulties.

For safety reasons therefore, the eye safe CO_2 laser would be a desirable source. This is due to the fact that the fluids in the eye are opaque to CO_2 laser radiation and hence stops it from reaching the retina. As a result, the maximum permissible exposure for intra beam viewing of the CO_2 laser is larger than that for other lasers. As a consequence, higher power levels can be utilized which as described within the range equation gives an improved performance.

4.7/ Laser Illuminators

4.7.1/ Advantages and Disadvantages

Before going into any detail into the various aspects of laser sources one should consider the advantages and disadvantages of such systems. As described previously, one of the useful features of a laser is its collimating feature (very low divergence). This allows a spot illumination of an object (providing it is greater than the size of the beam at the point of contact (see Table 4.2)).

The high spatial resolution, both angular and in range, which enables good pinpointing of the object under scrutiny is a second feature. Finally, the smaller antenna (telescope) requirements are a distinct advantage.

There is however a major disadvantage of laser systems and that has already been discussed - that of higher attenuation of signal transmission in various atmospheric conditions compared to microwave systems. This however is only significant in outdoor environments.

4.7.2/ Types of Lasers and Systems

Laser sources are now abundant in the visible, near infrared and far infrared regions[14] and these are the commonly used regions in radar systems. It is not possible within the scope of this report to detail all the features of the individual systems since the choice of particular items is dependent on the final requirements of the system. In Table 4.6 we have listed the companies who are claiming to be suppliers of commercial laser ranger/rangefinders[14]. Only one possible commercial active vision sensor has been identified to date, but no details are available[26].

Following from the atmospheric effects we can define specific regions where we should be operating: - We have concluded that we want to operate in an atmospheric window which effectively restricts us to the following bands: -

visible up to 1.4 μm

1.5 μm to 2.5 μm

3 μm to 4 μm

4.5 μm to 5.2 μm

8 μm to 14 μm

In addition, it may be possible to utilize the 40 μm to 1.22 mm region for short path lengths with lasers since there are limited atmospheric wind within this region (but the data is not as well documented), however the laser sou

are of the optically pumped type and are at present not considered a viable source for the application described.

In Table 4.7 we show the various laser systems available in the described regions in both cw and pulsed modes of operation. Although on the surface it would appear that a large number of systems may be available, many of the lasers mentioned are lab devices and are not readily available on the commercial market. In the wavelengths of interest it would appear that the following are possible sources: -

CO_2	Nd - YAG	Ruby
10.6 μm	1.06 μm	0.69 μm

Reference [14] lists in more detail all the variations on the above lasers and this should be consulted when making the final choice of laser source.

4.7.3/ Detection Systems

The choice of detectors used in any range system will depend on a number of factors:

wavelength of operation

mode of operation

signal levels expected

single element or array operation

Table 4.8 lists a recent survey of detectors and is a useful reference to base the detector choice on [27, 28].

4.7.4/ Telescopes and Detection Systems

Whereas in microwave systems antennas are used to transmit and receive signals, for laser systems the antenna is simply a telescope. It is

possible to either use separate telescopes for transmitted and received signals or to use a single telescope to perform both functions.

Diffraction limited telescopes with mostly reflective optics should be chosen. Typical telescope apertures are between 10 and 20 cm. The system used will have to be chosen to compliment the final application and laser used. As an example Fig. 4.4 shows a 13 cm telescope system used by the Lincoln Laboratory. The complete system is shown in Fig. 4.5.

In order to produce an image some form of scanning would be applied to the transmitted beam. It would be easier to position the scanning device in the image plane of the telescope to avoid manipulating large mirrors (required for the expanded and collimated beams).

Various methods of scanning have been identified and are listed [8]: -

Galvanometer (saw tooth driven) Scanners can give fields of views of 12 mR by 12 mR and are widely used and claim to give a high scan efficiency at frequencies of 100 - 200 Hz.

Rotating Polygon mirror scanners also have a high scan efficiency but are bulky at small angles of deflection (1° - 5°) and relatively low scan rates of laser radar.

Acoustic Optic scanners can be easily installed to give good scan efficiencies at slow scan rates but the drawback of such devices however is seen in the losses imposed on the laser output (up to 50%).

Further investigations would be required to select the appropriate scanner, but this gives some indication as to the possible directions. The scan efficiency of a Laser Radar Scanner (LRS) is the percentage of time the scanned laser is illuminating the desired image area. Thus the higher the scan efficiency the less average power required from the laser.

Most systems will use either a single detector or some form of linear array which can be scanned optically or mechanically to cover the field of interest.

4.8/ Applications

The previous discussion has concentrated on the operation of some types of laser systems which may be utilized. With this however, one should attempt to discuss some of the possible applications for laser systems in the fields of radar rangefinding. A brief summary along with some salient references will be given in order that the relevant works can be later investigated. Three main topics will be mentioned and these are:

Rangefinding

Imaging

Robotics

The discussions will be brief with the aim only to give some idea of the possibilities.

4.8.1/ Rangefinding

The major drive in rangefinding has resulted from military applications and as such the field is already well developed. Most of the systems are based on the mini TEA CO_2 laser and are reasonably compact. The companies selling such systems have already been given. Figure 4.6 shows a commercial rangefinder based on a TEA CO_2 laser [10]. This system, produced by Marconi Avionics claims an effective range of 11.5 km with an accuracy of ± 2 m (minimum range of 50 m). Typical configurations for laser radar type systems have been selected from the cited literature and

Figs. 4.7 - 4.9 show examples of these.

Figure 4.7 shows a diagram of a heterodyne detection imaging radar and shows the general relationship of the components[8]. Figs. 4.8 and 4.9 show the two forms of laser rangefinders which might be utilized [11]. Figure 4.8 shows the phase detection method of determining range. The second method, that of time of flight is shown in Fig. 4.9 (for pulsed systems). Such systems have been priced up to $25,000.00 (only for the ranging section)[11].

As an example of a practical system a wire obstacle warning system has been developed as a real time airborne sensor[29]. This system was developed for use in helicopters to give warning of obstacles such as 3 mm wires at ranges up to 300 m. The system used optical radar principles with a 30° (horizontal) by 9° (vertical) field of view and was based around a pulsed laser. In order to process range information into usable forms, some data regarding the signal form would be required. Most detectors which would be used will be giving some form of voltage output with phase or time delay information depending on the range technique used. The block diagrams which have been presented give the reader some indication as to the required techniques for each system (Figs. 4.8 and 4.9).

4.8.2/ Imaging

This field which for conveneince will be defined as producing a comprehensible picture of some object or scene, is also of interest to military users but would appear to be in the early stages of development. A number of articles related to imaging systems are referenced for completeness[6, 11, 13, 30 - 32]. The fields of imaging and robotics (4.8.3) are closely linked, with some form of imaging being required

before a robotic application can be implemented. A scan system over some region is required to build up a picture and by its very nature takes a finite amount of time. Some scenes have taken as long a 2 hours to construct [4] , with other scenes only taking a few seconds [11]. The time taken to construct an image can be lengthy for the following reason. To «build up» a picture comprised of say 128 elements one must have at least 128 laser shots. In addition it would appear that a certain averaging over each element is required (to improve picture quality). If we take a 10 shot average for each element we will thus require a total of 1280 laser shots. The number of pulses is limited by the repetition rate of the laser. For a TEA laser 1 - 10 pulses/second is common and so the described picture could take from 1280 sec. to 128 sec. to construct. Obviously with higher repetition rates the information gathering time will be less (1 KHz rep. rate - 1.28 sec). These higher repetition rates may be achieved with a Q switched laser. This obviously limits the active vision sensor to stationary targets and may be difficult to incorporate into a moving environment (see section 4.8.3.). Some of the drawbacks which have been linked to rangefinder type systems are[11]

1. missing information in a scene
2. computational complexity
3. time consuming to achieve good S/N
4. limited to indoor environments
5. limited to highly textured or line structured scenes
6. limited surface orientation
7. limited spatial resolution.

Not all of these drawbacks will apply to one system, but some will have to be considered in any final system. Some of the applications already found for imaging systems have yielded pictures, in frames of 64 by 64 or 128 by 128 rangepics (see 4.8.3), of stationary objects in indoor

environments. Figure 4.10 shows some examples of the composed pictures[11] and which took between 4 and 40s to compose.

4.8.3/ Robotics Applications

A number of reports on this field have been located [3, 4, 33] and initial impressions are that the technology (in an experimental form) is available, but as for the imaging case, slow information gathering times are st a problem. A review of the applications which have been investigated will be given, but first a description of the terms used in such discussions should be presented:

One term commonly used to define an image is the rangepic and this is an array of distance elements from a known point or plane with adjacency constraints corresponding to those of 2D intensity imagary. For more information the references should be consulted. As a result of the slow processing times described previously (4.8.2), the robotics systems investigated tend to use TV systems for overall scene analysis and a laser source to give depth information.

Some of the applications found and investigated by one group will now be described[3]. The programme was concentrated on the various techniques required to move a vehicle around some remote location and for some tasks to be performed without detailed human interaction. The Laser Rangefinder was part of a vision system which also included two television cameras and a microcomputer. These applications will now be described:

a) Rockfinding: The system was developed to enable automatic scanning, recognition, position and orientation determination and retrieval of the tallest rock in a 30 cm by 70 cm scanned region.

b) Vehicle Obstacle Scan: A side to side laser scan was used as an in-motion early warning obstacle detector for vehicle motion. A beam was swept along a line 3 metres in front of the vehicle at ground level and

sharp differences in the range data were sought. The criterion for an obstacle was taken as follows: If a range difference of 7.8 cm or greater existed between successive points then the vehicle was stopped to enable more data to be gathered. Since however a scan took 2 seconds (94 points at 50 points per second), the speed of the vehicle had to be restricted.

c) Obstacle Mapping: In this case a laser radar rangefinder was used to map the terrain in the vicinity of the vehicle and a «picture» of safe and unsafe regions displayed on a map. This is shown in Fig. 4.11 where the safe regions are grey, unsafe white, and unknown in black.

d) Finally, actual pictures have been produced using the laser radar rangefinder using rangepic information. Figures 4.12 and 4.13 show two such examples with lighter regions being closer to the source.

4.9/ Alternative Methods

4.9.1/ Laser Holography

For completeness, other vision schemes should be described within this review. One of these remaining techniques which have not yet been treated is that of laser holography.

This technique can be summarized as a coherent image forming process in which a record is made of the interference pattern produced when diffracted radiation from an object of interest interferes with a coherent reference beam. The intensity distribution in this interference pattern is the hologram and it has the property that when it is illuminated in the correct fashion the original wavefront is reconstructed and an image can be formed of the original object. Detailed descriptions of the holographic methods will not be given here, but only referenced[34]. The image formed by this technique is a 3 D image (since phase information is recorded).

Some of the applications of image forming holography which have been identified are: Microscopy for particle size analysis; pulsed laser

photography; microcircuit manufacture; and data storage and retrieval. Non image forming applications of holography are: interferometry for non destructive testing and contour generation. Non Destructive testing can be used to determine flaws in objects (the flaw is seen as an anomaly in the fringe pattern). The flaws could be cracks or weak areas in the object and the procedure is to make a hologram of an object, then «stress» the object in some manner and observe any anomalies in the observed fringe pattern. A report entitled «Holographic NDE Status and Future» may be a worthwhile report to obtain and is published by the National Bureau of Standards[35].

4.9.2/ Imaging and Range Finding by Triangulation

A simple means of forming an image, and determining the distance to each object point in it, is triangulation on a small spot of light (visible or infrared) which scans the image area. The light source might be an LED or a laser. The detection is performed by a detector capable of measuring the angular position of the spot of light, by (a) searching for it (b) tracking it or (c) using an array of detectors. If the angular direction of the beam at any instant is known, only one such detector is needed. If the angular direction of the beam is not known accurately, two detectors will be needed.

Jarvis[11] has described an experiment in which the infrared range finding components from a Canon AF 35 mm camera were used to produce a 64 x 64 image in which the range to each point in the image was known (i.e., a rangepic). Because he used an XY pen plotter to do the scanning (which was done by translation rather than rotation of the source in this case) the scanning time was very long. A system could be designed to do the same job in much less time.

The use of infrared eliminated problems due to interference from ambient light.

This approach offers the possibility of a very inexpensive system, for relatively short range applications. One drawback to triangulation is that, because the source and detector are separated, some points in the object may not be simultaneously visible to both. Thus, there may be some missing points in the image.

4.10/ Conclusion

The possibility of using laser technology for ranging and active vision sensing applications has been discussed. After considering atmospheric and safety effects it would appear that a laser in the 10 μm region would be the most likely candidate for the applications described.

The extremely low divergence of lasers leads to the fact that small object areas can be imaged, which is a distinct advantage over millimetre type systems.

Ranging of objects would appear to be feasible with CO_2 lasers but imaging for identification purposes is still difficult to achieve in short time periods due to the time taken to build up an image (limited by resolution required and repetition rate of the laser).

The choice of laser for a ranging type application for outdoor environments would appear to be a TEA CO_2 or Q switched CO_2 laser. A further study on the particular characteristics required and the feasibility of such systems would have to be performed in a separate study programme.

4.11/ References

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		Relative Speed kmh^{-1}			
λ	f (Hz)	0	80	160	320
		F_D	F_D	F_D	F_D
1.22 mm	2.459×10^{11}	0	36 KHz	72.1 KHz	144.2 KHz
118.8 μm	2.525×10^{12}	0	370 KHz	740.6 KHz	1.481 MHz
10.6 μm	2.83×10^{13}	0	-4.15 MHz	8.3 MHz	26.6 MHz
1.06 μm	2.83×10^{14}	0	41.5 MHz	83 MHz	166 MHz
0.6328 μm	4.74×10^{14}	0	69.5 MHz	139 MHz	278 MHz

Table 4.1/ Doppler Shift for Various Relative Speeds

Wavelength	Distance from Transmitter (metres)					
	5	15	40	130	300	500
1.22 mm	0.07	0.22	0.595	1.94	4.39	7.44
118.8 μm	0.007	0.022	0.058	0.188	0.435	0.72
10.6 μm	0.00006	0.0019	0.0052	0.0168	0.039	0.065
1.06 μm	0.000006	0.00019	0.0052	0.0017	0.0038	0.0065
0.6328 μm	38.6 μm	1.15×10^{-4}	3.8×10^{-4}	1×10^{-3}	0.0028	0.0038

Table 4.2/ Minimum Resolution Through Diffraction Limit for a 10 cm Aperture

Condition	Infrared	Visible
Daylight Zenith	2 (45° Elevation)	8 (Zenith)
Night	8 (0° Elevation)	10^{-5} (Zenith)

Table 4.3/ Background Spectral Radiance $N_b(\lambda)$
(W_m^{-2} Sr^{-1} μm^{-1})

λ (micron)	Rayleigh a_λ (km^{-1})	a_λ^{Mie} (km^{-1}) V = 1 km	V = 5 km	V = 10 km
0.2	0.70	7.0	2.2	1.4
0.3	0.14	5.6	1.4	0.84
0.4	0.44	4.7	1.1	0.58
0.6	0.0083	3.7	0.72	0.35
0.8	0.0026	3.1	0.54	0.24
1.0	0.0006	2.8	0.43	0.18
5.0	0.000001	1.1	0.086	0.024
10.0	0.00000006	0.72	0.043	0.010

Table 4.4/ Rayleigh and MIE Scattering Coefficients

Laser Type	Primary Wavelength(s) (nm)	Protection Standard	
		Eye	Skin
Helium-Cadmium Helium-Neon Argon Krypton Frq. Doubled Nd YAG	441.6 632.8 488 514.5 647.1 532	a) $2.5 mW \cdot cm^{-2}$ for 0.25s b) $10 C_A mJ \cdot cm^{-2}$ for 10-10 000s c) $C_A W \cdot cm^{-2}$ for $t > 10\,000s$	$0.2 W \cdot cm^{-2}$ $0.2 W \cdot cm^{-2}$
Neodymium YAG Gallium Arsenide at room temp	1.064 905	$1.6 mW \cdot cm^{-2}$ for $t > 100s$ $0.8 mW \cdot cm^{-2}$ for $t > 100s$	$1.0 W \cdot cm^{-2}$ $0.5 W \cdot cm^{-2}$
Helium Cadmium Nitrogen	325 337.1	a) $1 J \cdot cm^{-2}$ for 10 to 1000s b) $1 mW \cdot cm^{-2}$ for $t > 1000s$	a) $1 J \cdot cm^{-2}$ for 10 to 1000s b) $1 mW \cdot cm^{-2}$ for $t > 1000s$
Carbon-dioxide (and other lasers 1.4μm to 1000μm)	10.6μm (10 600nm)	$0.1 W \cdot cm^{-2}$ for $t > 10s$	$0.1 W \cdot cm^{-2}$ for $t > 10s$

[indicates a) b) and c) apply to each laser type in the grouping

Table 4.5/ Intrabeam Protection Standards which are Applicable to Many Common CW Lasers for Eye and Skin Exposure to Laser Radiation

Laser Type	Primary Wavelength(s) (nm)	Pulse Duration	Protection Standard	
			Eye	Skin
Normal pulsed ruby	694.3	~ 1ms	$10^{-7} J \cdot cm^{-2}$	$0.2 J \cdot cm^{-2}$
Q switched ruby	694.3	5-100ns	$5 \times 10^{-7} J \cdot cm$	$0.02 J \cdot cm^{-2}$
Rhodamine 6G Dye Laser	~ 500-700	0.5-100μs	$5 \times 10^{-7} J \cdot cm^{-2}$	$0.03-0.07 J \cdot cm^{-2}$
Normal Pulsed Neodymium	1064	~ 1ms	$5 \times 10^{-5} J \cdot cm^{-2}$	$1.0 J \cdot cm^{-2}$
Q switched neodymium	1064	5-100ns	$5 \times 10^{-8} J \cdot cm^{-2}$	$0.1 J \cdot cm^{-2}$

Table 4.5.1/ Intrabeam Protection Standards which are Applicable to many Pulsed Lasers for Eye and Skin Exposure to Laser Radiation

Table 4.6/ Commercial Suppliers

RANGEFINDERS, MILITARY

Associated Controls & Comm.
CILAS-Alcatel Compagnie Indust.
CLS Industries Inc.
Contraves Georz Corp.
EL-OP
Elomag
Ericsson Radio Systems AB
Farrand Optical Co. Inc.
Ferranti pic
GSG Laser SRL
Honeywell Systems & Res. Ctr.
Hughes Aircraft Co. IP
Internation Laser Systems
Kazuko Enterprises Inc.
Laser & Electro-Optical Sys.
Laser Photonics Inc.
Marconi Avionics Inc.
Marconi Avionics Ltd.
Optel Gesellschaft
Selenia Industrie
SOPELEM

RANGING, CONSTRUCTION

Associated Controls & Comm.
CILAS-Alcatel Compagnie Indust.
CLS Industries Inc.
CR Laser Corp.
EL-OP
GSG Laser SRL
Iker Inc.
Laser Applications Inc.
Laser Photonics Inc.
Marconi Avionics Inc.
Metrologic Instruments Inc.
Muffoletto Optical Co. Inc.
Multilasers
Optech Inc.
Prismoid Optical
Simulaser Corp.
WEC Corp.
Yool Engineering

LASER SYSTEMS , RANGING

Associated Controls & Comm., Inc.
CBL Optronics
Cilas-Alcatel
CLS Laser Systems Inc.
Diffracto Ltd.
EL-OP Electro-Optics Industries Ltd.
Ferranti Electro-Optics Inc.
General Electric
GSG Laser srl
Harris Corp.
W.C. Heraeus GmbH
Holograf
Iker Inc.
International Laser Systems Inc.
Kazuko Enterprises Inc.
Laser Photonics Inc.
Laser Science Inc.
Magnavox Electro-Optical Systems
Marconi Avionics Inc.
Multilasers
North China Rsch. Inst. of Electro-Optics
Optel Ges. f. Lasertech. u. Electr. mbh
Polytec GmbH
Selective Electronic Inc.
Space Optics Research Labs
United Technologies Research Center
United Technologies Research Ctr.
Varo Inc.

LASER MEDIUM	LASER TYPE	OPERATION	GENERAL WAVELENGTH REGION (μm)	COMMENTS
Solid State	Ruby Nd-Yag Nd-Glass Alexandrite Erbium Doped-YLF Holium Doped-YLF F-Centre	cw/pulse	0.263 - 3.2 (UV - Near Infrared)	
Semiconductor	GaAℓAs GaAs InGaAsP Lead Salt	cw/pulse	0.75 - 1.6 (Near Infrared)	
Gas	H_2O, XeF, ArF N_2O, XeCℓ, Ar N_2, HeF, HeNe KrF, HeXe, HeCd KrCℓ, CO, Ar/Kr, HF, DF, CO_2, F, Cu, Au FIR Lasers	cw/pulse	0.157 - 1200 UV, Visible to Far Infrared (Incl. IR)	Some optically pumped
Dye	Various Media	cw/pulse	0.19 - 3 (UV - Near Infrared)	Optically pumped

Table 4.7/ Laser Wavelengths Available

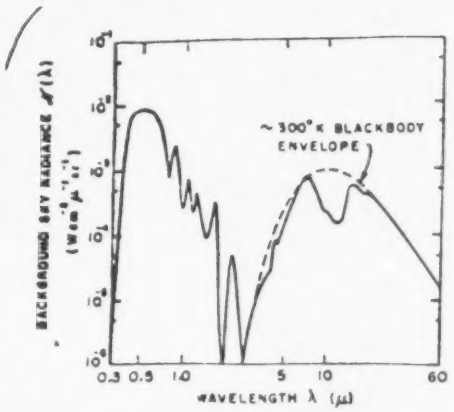


Figure 4.1/ Spectral Radiance of the Sky Under Clear Daytime Conditions

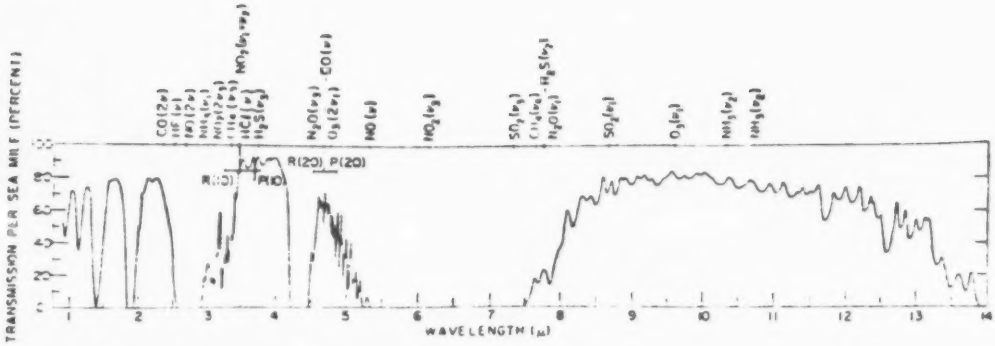


Figure 4.2/ Atmospheric Transmission

Atmospheric transmission in the 1 to 14 μm region of the infrared together with the important absorption bands of molecular pollutants (visual range is 14 km and water content is 17 mm/nmi which corresponds to a relative humidity of 70 percent at 60°(F)).

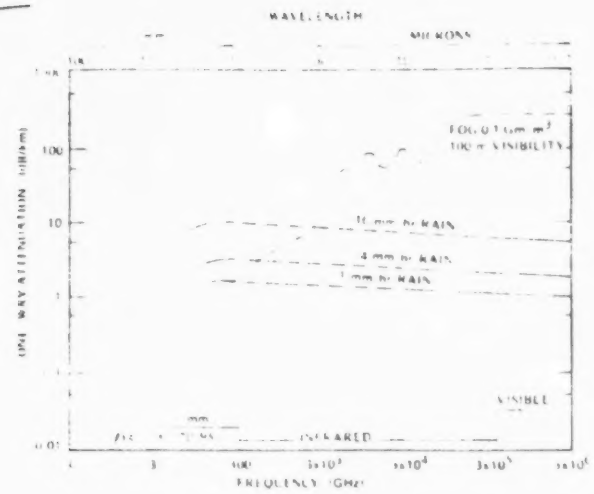


Figure 4.3/ Effects of Rain and Fog

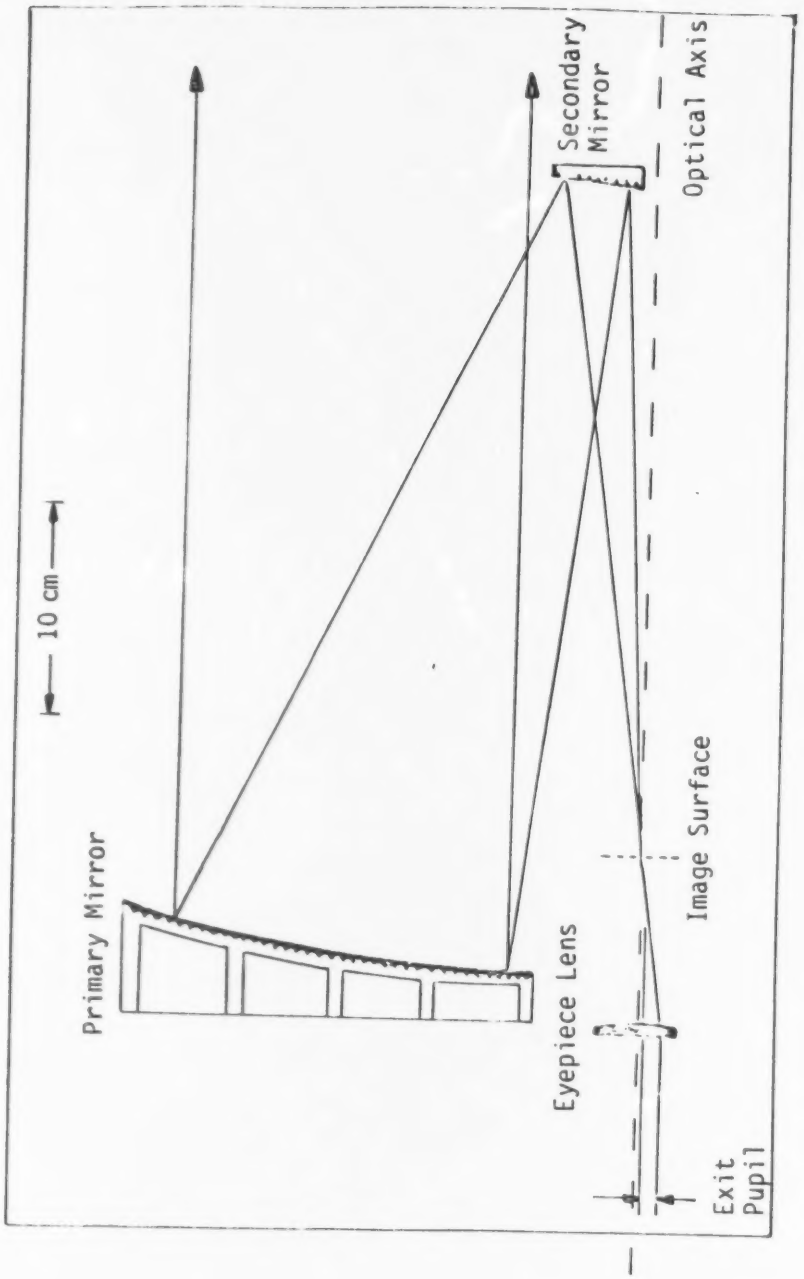


Figure 4.4/ The 13 cm Telescope used in Lincoln Laboratory System

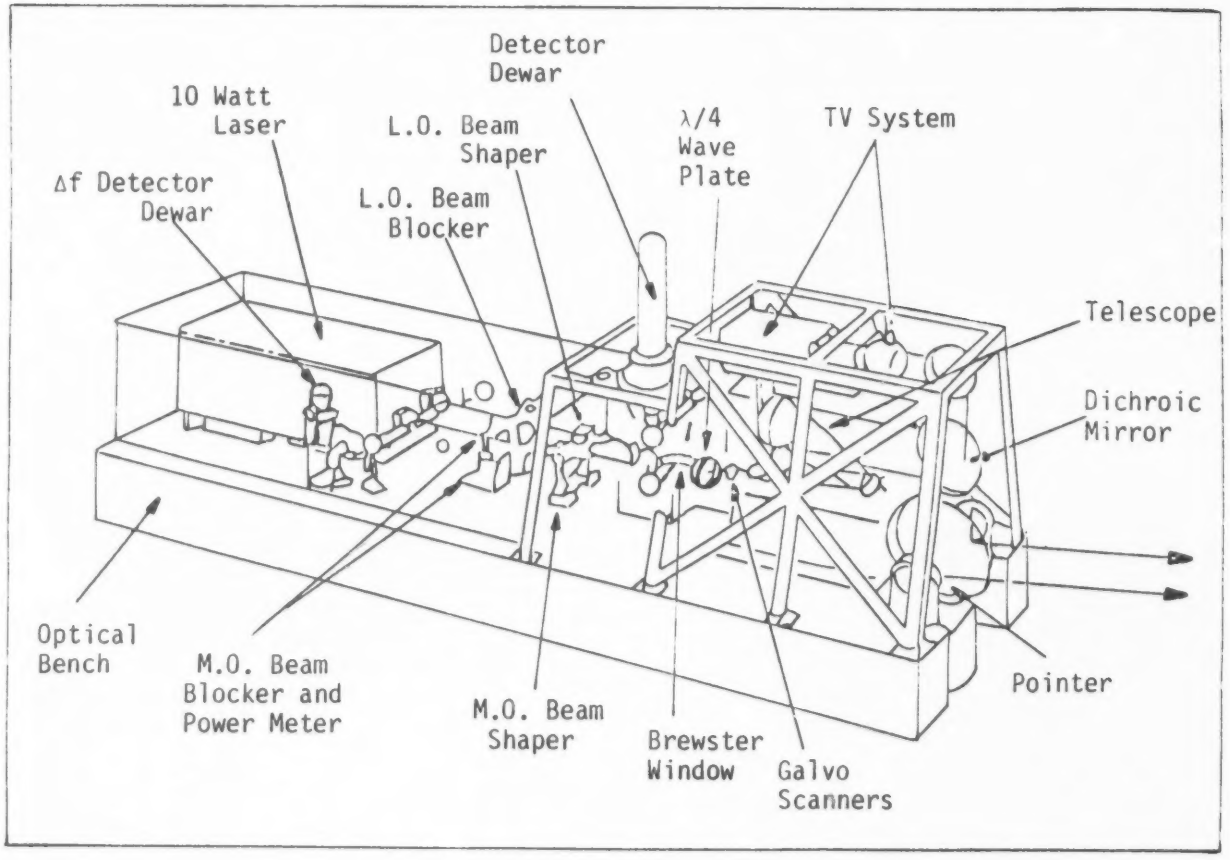


Figure 4.5/ Transportable pulsed Infared-Laser used in Lincoln Laboratory

Figure 4.6/ Commercial Range Finder

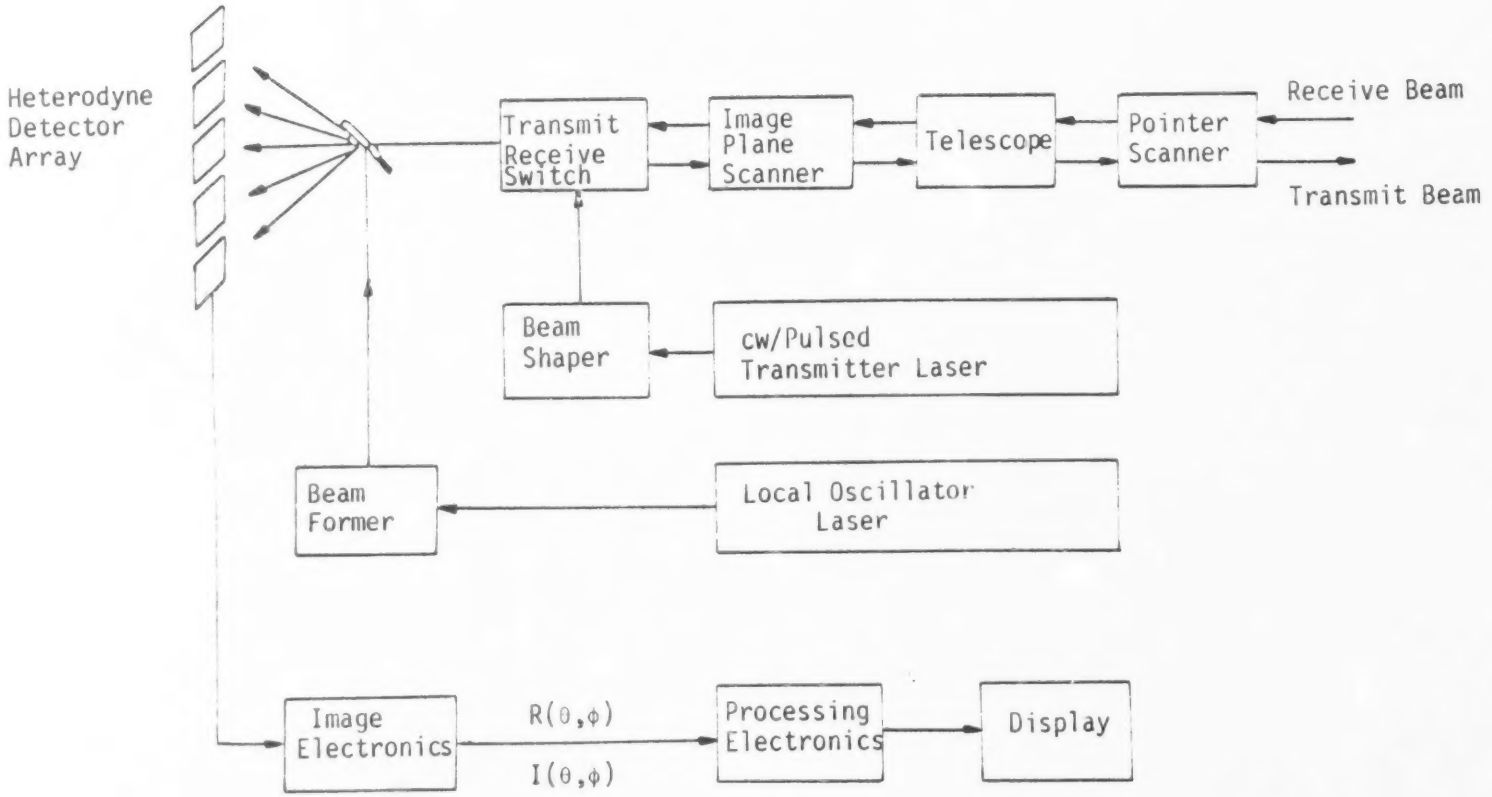


Figure 4.7/ Typical Configuration of Heterodyne Laser Radar

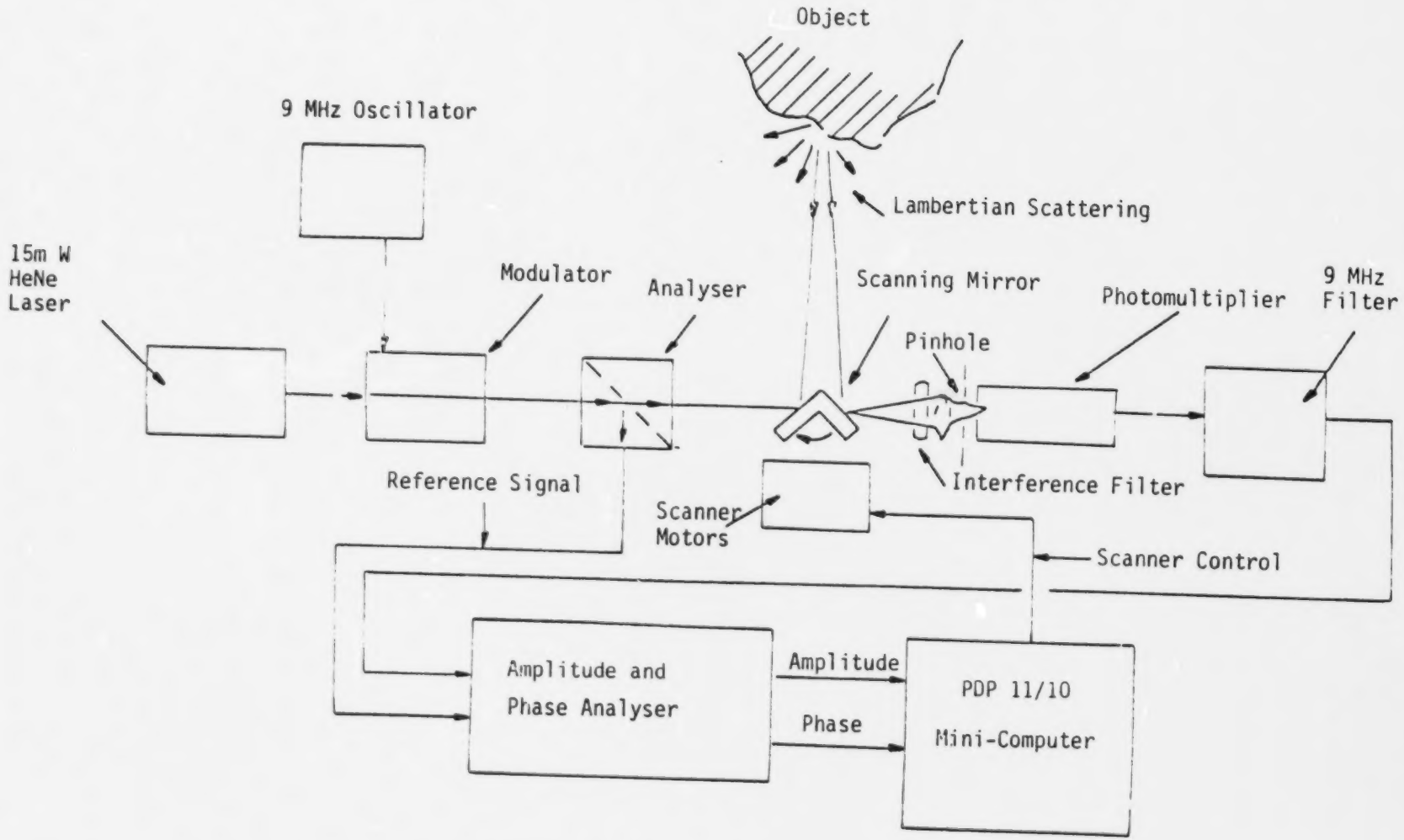


Figure 4.8/ Phase Detection Laser Range Finder Block Diagram

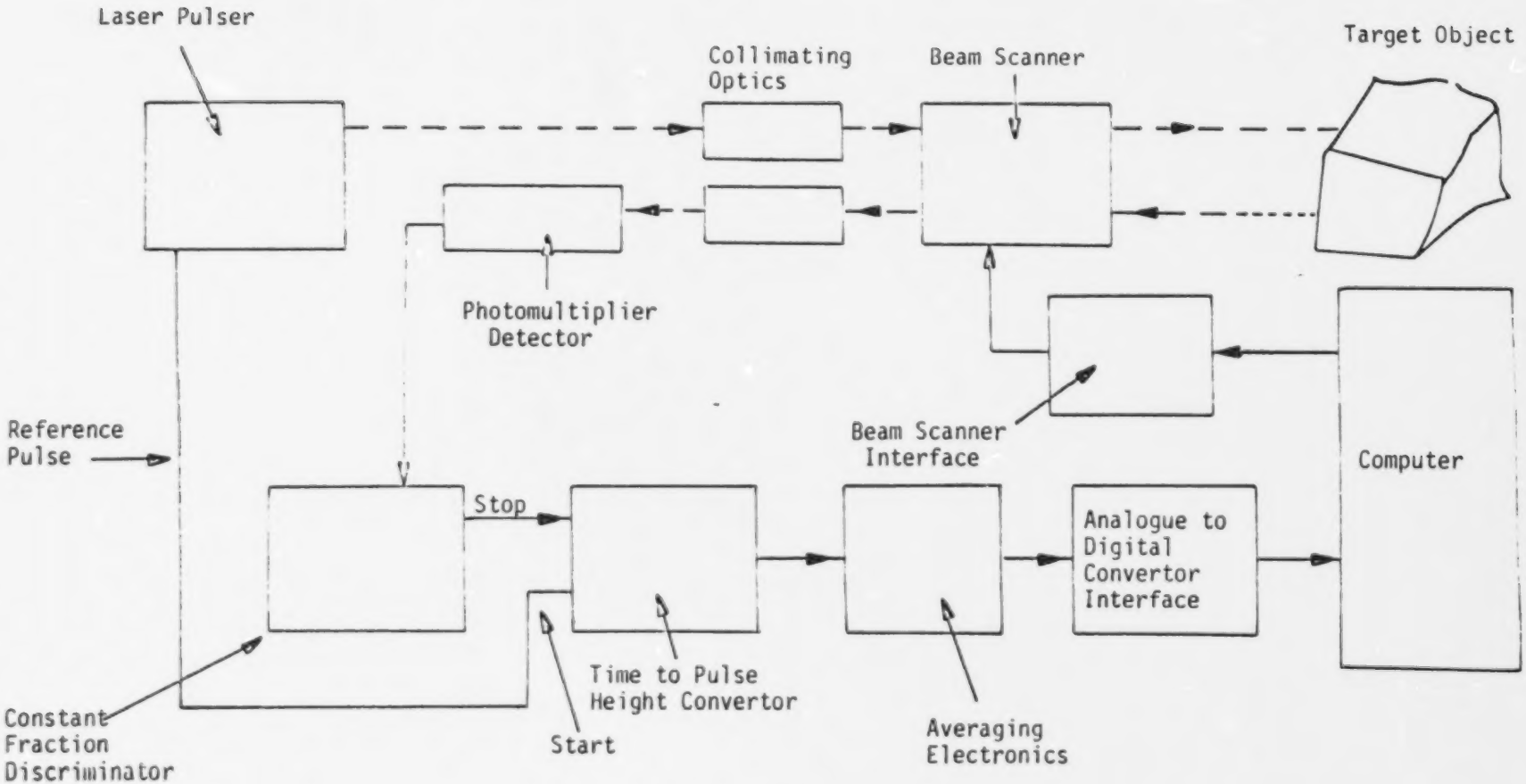
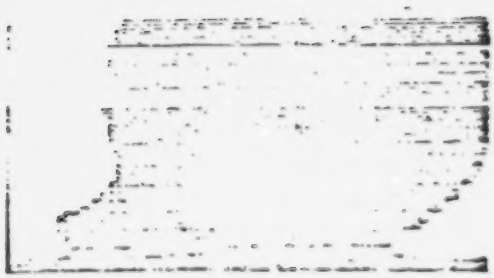


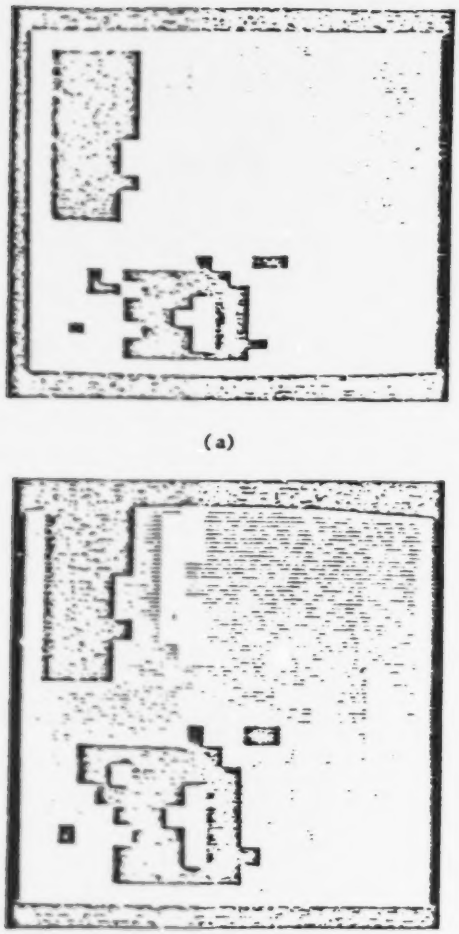
Figure 4.9/ Time-of-Flight Laser Range Finder Schematic



Rangepic of a 6 in. funnel (64 x 64, 100 samples/point).

Rangepic of right hand (64 x 64, 100 samples/point)

Figure 4.10/ Rangepic of 6 inch Funnel and Rangepic of a Right Hand



(a)

(b)

Figure 4.11/ Obstacle Map

Obstacle Map (Safe regions in grey, unsafe in white, and unknown in black).

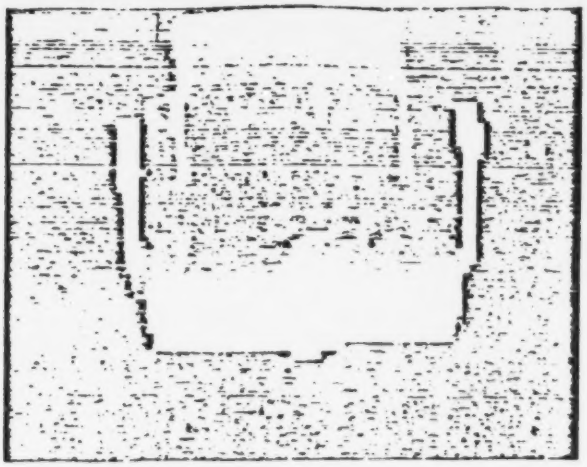


Figure 4.12/ Rangepic of a Chair (lighter regions closer)

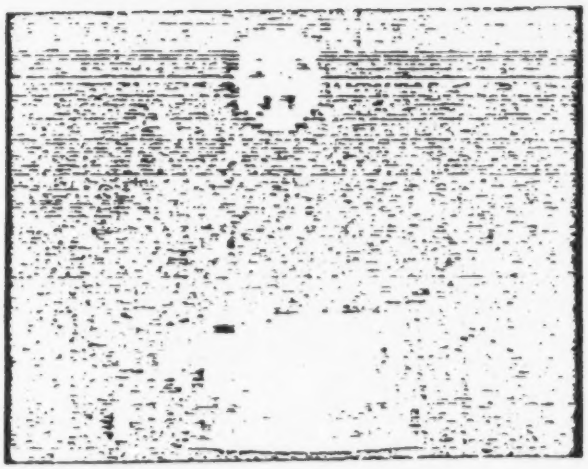


Figure 4.13/ Rangepic (lighter regions closer)

5/ DIGITAL SIGNAL PROCESSING

5.1/ Introduction

This section describes the processing and analysis of the various image types produced by the active vision sensors and proposes applications relevant to the transport area. The types of images to be considered are:

a) Reflectivity images. These are two-dimensional images (x vs y) repesenting intensity of the energy reflection. The intensity is a function of a number of factors, such as distance, surface reflectivity, surface orientation, path attenuation, etc. as described in preceding sections.

b) Plan Position Images (PPI). These are images created by plotting time of maximum echo vs scanning angle. Echo time is proportional to distance.

c) Range images. These are two-dimensional images (x vs y or O vs o) representing echo time (or distance). These are essentially series of plan images.

d) Wide beam images. These are two-dimensional images representing return intensity as a function of time and scanning angle, produced from a beam which is narrow in one dimension and wide in the perpendicular direction.

We assume that any processing required on the raw data, eg convolution on an echo response, has been performed. We assume

that, for PPI and Range images, the echo time (or distance) is the time of the maximum response. The processing and analysis to be described will be with a view towards the applications.

This section closes with a discussion of hardware required for the processing.

5.2/ Reflectivity Images

5.2.1/ Image Characteristics

Reflectivity images are two-dimensional images representing intensity of the energy reflection. They are in many respects similar to conventional TV images except for the frequency of electromagnetic energy used. The main advantage of NMMW images of this sort over conventional TV images is the ability to penetrate fog and smoke, although the resolution, signal to noise ratio, and other artifacts such as speckle and glint make the image much inferior to conventional TV in non-fog situations. Processing of these images is similar to that of conventional TV images, for which (1), for example, may be referenced.

5.2.2/ Image Processing and Analyses

Several image processing techniques may be applied to NMMW images (2). These include:

a) Resolution enhancement. Because the image formed by an optical system is the deconvolution of the object with the point spread function of the optics, in principle the object can be restored

from the image by mathematically inverting the convolution process. In practice, it is noise in the image and uncertainties in the point spread function that limit the deconvolution process.

b) Non-linear recording. In order to suppress glint, the image is recorded with a non-linear grey scale, which suppresses the higher intensities in the image.

The achievements in computational image analysis in the last few years have been possible in closely controlled enviroments, performing relatively simple processing on "clean" images. In the transport area applications, the environment is not controlled, and "complicated and noisy images ... are expected in practice" (2). Image analysis techniques are too immature to apply to this situation, and therefore this mode of imaging will not be considered any further.

5.3/ Plan Images

5.3.1/ Image Characteristics

This type of image consists of distance vs scanning angle, and may be obtained from sweeping a radar beam and plotting time to maximum return vs sweep angle, or may be obtained by triangulation techniques in which the illuminating spot and receiver lie in the same plane. This type of display is commonly used to display aircraft position.

5.3.2/ Image Processing and Analyses

If necessary, the signal may be smoothed, perhaps using a median filter, to eliminate the effect of noise. It may be desirable to transform the data from polar to rectangular coordinates for analysis purposes, although this is probably not required. Figure 5-1 illustrates the relationship between the coordinate systems. It is unlikly that any object identification will be attempted based on the shape of the portion of an object cross-section facing the scanner. A better use of the data is the detection of obstacles.

5.3.3/ Applications

5.3.3.1 Obstacle Detection

Consider such an imaging device scanning horizontally, parallel to the track, at height h above the track. The processing task is to ensure that no echos are returned which would indicate an object lying within the guideway. If such an echo is detected, the

angular width of the object must be determined, which, used with the distance information, would give an estimate of its cross-sectional size at height h. The angular width may be determined by the number of adjacent points lying within the guideway region. Several such scanners at various heights could be used. For example, a low scanner might not detect an animal's legs, but a higher scanner would detect its body. This system could be used to watch a stretch of track or a level crossing.

Let us consider the case in which a section of track is being monitored. There are a number of factors which will influence the length of track that may be monitored. The first is the track layout and the surrounding countryside. A track which curves or which rises and falls has different scanning limitations than a straight, flat track. Another problem is the placement of the scanner - it must be placed so that it will have an unobstructed view of the track, with no trees in the way, and snow cleared from its view. If the track is flat and straight, and the scanner is unobstructed, the scanner's attributes will limit the length of track to be monitored.

Horizontal beam width. Figure 5-2 shows the relationship between the beam width o required to cover an object of width w located at distance d along the track, which is located at unit distance from the scanner. Each scanner has a beam width which, combined with the minimum object size to be detected and the distance of the scanner from the guideway, determines a maximum usable distance.

Vertical beam width. The vertical spread of the beam limits the

length of track that may be scanned. If the scanner is at height h, and the vertical spread is of v radians, where v is relatively small, the beam will begin to strike the ground at a distance of about 2h/v from the scanner.

Position accuracy. If the angular position of the scan has an error of d0/2, the accuracy with which the obstacle may be located on the track is affected. Fig 5-3 shows the relationship between distance uncertainty as a function of distance and d0.

Signal noise. The effect of noise on the signal is to make the detection of the returned pulse less certain. A false pulse may be detected, the true pulse may disappear, or appear to start earlier or end later.

5.3.3.2 Mobile Robot

A mobile robot may be equipped with a rotating sonar sensor, providing it with a plan image of its environment. Mobile robots may use sonar either simply to avoid collisions (3), or for path planning, obstacle avoidance, learning and path execution (4). The art of mobile robot control, particularly in uncontrolled environments, is in its infancy, and cannot yet provide techniques useful outside the laboratory environment.

5.4/ Range Images

5.4.1/ Image Characteristics

This type of image consists of range or distance information as a function of x and y (or θ and φ). It may be obtained by radar or triangulation technique with a narrow beam. It may also be thought of as a series of plan images of adjacent planar sections. This type of image, though superficially similar to the reflectivity images, is really quite different, and, in general, image processing techniques suitable for reflecivity images are not suitable for range images, particularly those that alter the pixel values.

5.4.2/ Image Processing and Analyses

There are relatively few papers in the literature dealing with the analysis or interpretation of range data. For example, the selection of papers on range data analysis at the recent Seventh International Conference on Pattern Recognition gives an example of the state of the art. Vemuri and Aggarwal (5) discuss a technique of subdividing range data into regions separated by jump boundaries (occluding or occluded edges) and internal edges (high curvature). Muller and Mohr (6) discuss detection of planar and quadric surfaces. And Faugeras (7) discusses segmenting the data into regions, then matching the data to a rigid model using the planar regions of the data as keys to the model. These papers are representative of the work in this area. There are also a few cases in which range data is combined with conventional images,

eg. (8), (3).

5.4.3/ Applications

Given the current state of the art, it is rather premature to hypothesize object identification capabilities in the near future. Obstacle detection, however, seems feasible.

5.4.3.1/ Obstacle Detection

Let us consider the case in which a scanner is located above the guideway, either on a vehicle or on a stationary mount. The range data that one expects for a portion of track is known in advance. The processor must verify that the range data acquired matches the expected. This may be done be subtracting the expected results from the acquired data; any difference above the noise level in the portion of the image representing the guideway represents an obstacle. Its location is known, and the number of picture elements (and which elements) it occupies gives some size information. Figure 5-4 shows the horizontal scan angle required to scan a guideway of width w as a function of 0, the angle with respect to the vertical, for a straight flat guideway. It also shows the distance to the track as a function of 0. This gives an idea of what the guideway data would look like if a linear scanning technique is used.

There are several aspects to be considered which limit the length of track that may be monitored by a single scanner. Figure 5-5 shows the effect of beam width angle as a function of the width of the obstacle to be detected and its distance from the scanner,

assuming that the obstacle is in the center of the guideway.

Figure 5-6 shows the vertical beam width required to resolve objects situated on the guideway. The effect of uncertainty of the scanner position 0 is shown in Figures 5-3 and 5-7. Figure 5-3 shows the uncertainty in the location of the beam position along the track. In Figure 5-7, the ranges determined from erroneous values of 0 will be interpreted as obstacles of height dh1 or holes of depth dh2. The range of height error is shown for various errors in 0 as a function of location along the track.

Considering the relatively low height of the train, the increased inaccuracy of information at greater distances, and the errors introduced by movement and vibration of the train, mounting a scanner on a train is not a likely possibility. A stationary scanner watching a section of guideway is more likely. The processor associated with the scanner would be "taught" what its section of track should look like, and possibly how to control the scanners so that not too much extraneous data is collected.

5.5/ Wide Beam Images

5.5.1/ Image Characteristics

These are two-dimensional images representing return intensity as a function of angle. Essentially, the complete returned signal as a function of time is saved for each scanning angle. Instead of using narrow beams as for the other images, a wide beam is used to collect the data along a vertical or horizontal path.

5.5.2/ Applications

Two possibilities, a longitudinal and transverse beam, are possible. We will discuss the problems with the longitudinal beam, and discuss two variants of the transverse beam in more detail.

5.5.2.1/ Longitudinal Beam

In this application, the scanner is positioned above the guideway and scans a longitudinal beam across the width of the guideway. The idea is that the amplitude vs time characteristics from a single scan should have a fixed shape: a diminishing amplitude for increasing time (see Figure 5-8). An obstacle on the guideway would result in a local deviation from this pattern. The overall amplitude may vary according to atmospheric conditions. In practice however, the effect of variable ground cover may be very dramatic. A clump of snow, fall leaves, change of vegetation in spring, the wetting of the ground by rain, will all affect the returned signal differently, resulting is an uneven signal in

which it may be impossible to locate an obstacle.

5.5.2.2/ Simple Transverse Beam

In this application, the scanner is positioned above the guideway and scans a transverse beam along the length of the guideway. The width of the scan must be altered for different scan positions so that only the guideway is scanned, the scan narrowing as further distances are scanned. If the guideway is flat, the expected response is a single peak whose position is related to the distance to the ground and whose amplitude, so long as it exceeds the noise level, is irrelevant (Figure 5-9). An obstacle which completely covers the scanned width will result in a shifting of the peak toward the origin, because the time for the return is decreased. An obstacle which partially covers the beam width will result in a multiple or blurred peak, with the new signal being nearer the origin, and the expected peak being attenuated. An estimation of the width of the obstacle is difficult, but in ideal conditions it is related to the diminution of the return amplitude at the expected location. Some idea of the shape might be obtained by combining the time of the beginning of the obstacle return signal with the scan angle. This profile could also be obtained as follows: the object is projected onto the 2-dimensional plane which runs vertically through the center of the track to the scanner, and the points on the profile visible to the scanner are marked. The location along the track is determined from the scan angle.

Many of the analyses presented earlier apply to this method. The

effect of error in scan angle 0 affects the accuracy with which the obstacle may be located along the track (Figure 5-3) and the apparant height of the obstacle (Figure 5-7). The width of the beam is a function of the distance scanned (Figure 5-5). The longitudinal beam width limits the size of object that can be resolved at a given distance (Figure 5-6). And the effect of the signal noise is the same as for the other cases - detection of signals is uncertain.

Banked curves present a serious difficulty to this method. The expected return is no longer a single peak but a wide peak corresponding to the range of depth observed by the scanner. Because of the diversity of return amplitudes possible, in general obstacles which lie within the minimum and maximum depths cannot be detected. One might develop clever schemes to compare the signal returned with what is usually returned, or what was returned a short while ago, or what is returned at other scan angles, but these schemes will have some risk associated with them. Presumably banked curves represent a small percentage of a track length so special techniques can be used at these locations. For example, a beam tilted so that every point of the beam reached the ground at the same time would solve the problem.

The processing required for the data consists of finding the earliest time at which the return signal is significant and comparing this time to the expected return time. If it arrived too early, an obstacle has been found. If adjacent scans also detect the obstacle, some aspects of its shape (such as height)

may be determined.

5.5.2.3/ Compound Transverse Beam

This is a variant of the previous simple transverse beam method, and addresses the problem of changing the scan width according to the location being scanned. The idea is to replace the single, variable-width beam with multiple scanners of fixed width. These are arranged such that the scanner footprints are adjacent immediately below the scanners. At distances further from the scanner, the footprints overlap, and spread out beyond the guideway. At these distances, the outermost scanners may be ignored. For scanners at height h with a footprint of size w below the scanner, the footprint at distance d away from the scanner is given by w*h*sqrt(h*h + d*d). If d>>h, this is approximated by w*h*d. Figure 5-10 illustrates the use of five scanners. Sensors 1 to 5 are required in the region d<d1. Between d1 and d2, data from sensors 2 and 4 may be ignored if desired, as their scan areas are completely covered by other scanners. At d2, the scan widths of sensors 1 and 5 become unacceptably wide, and data from these sensors is ignored for distances beyond d2. Sensors 2 and 4 now scan the edges of the guideway. At d3, the scan widths from sensors 2 and 4 are too wide, and their data is ignored. Sensor 3 alone is used from this point to d4, when its beam is too wide.

The scanner outputs may be considered individually or combined to form a single output to be processed. The former is obviously

more work than the latter, but has several advantages: a) the relative strength of a signal occurring in a single channel to the noise level is greater than if all channels had been combined, and b) confirmation of results may be done in certain instances, eg. in region d2 to d3 of Figure 5-10, an object indicated by sensor 5 should also be indicated by sensors 2 and/or 4. In either case, the processing of the signal is the same as for the variable-width single transverse beam described earlier.

5.6/ Image Processing Hardware

5.6.1/ Processing Requirements

The processing required to analyze the input images to produce output giving the location and some size information of an obstacle is relatively simple. It consists first of comparing the data with known or expected data. If the difference exceeds some threshold (which may be a function of scan angles), the location of the obstacle is then determined. If the scanners are not mounted on a vehicle, processing time is less critical, possibly on the order of seconds or even minutes, and may possibly be performed by a single microprocessor without the use of any special-purpose processors.

5.6.2/ Commercially Available Hardware

If special-purpose hardware is required, an array processor (AP) should be the first device to be considered. An AP allows operations on one-dimensional arrays (eg sum, maximum, minimum), on pairs of arrays (eg point-by-point multiplication, addition, comparison), or on an array and a scalar (eg multiplication, addition by a scalar, comparison). Most of the processing requirements considered here can be put into this format. An AP would substantially improve processing time. Several manufacturers of AP's are: Analogic Corp (Wakefield, Mass.), Ariel Corp (New York, N.Y.), CSP Inc (Billerica, Mass.), DSP Systems (Ottawa, Ont.), Floating Point Systems (Beverton, Ore.), Numerix Corp (Newton, Mass.), Sky Computers (Lowell, Mass.), Star Technologies

Inc (San Jose, Calif.).

A number of special data processing chips such as the TI TMS 320, NEC uPD7720, and AMI S2811 might also be useful for some of the processing. A review of current digital signal processing hardware and software may be found in (9).

Several image displays are able to perform calculations over entire two-dimensional images, eg. addition and multiplication of images, convolution, maximum and minimum values. These might be useful for processing of range data obtained from a two-dimensional scan. Several manufacturers of display equipment with these capabilities are: Grinnell Systems (San Jose, Calif.), Comtal (Altadena, Calif.), Gould DeAnza (San Jose, Calif.).

5.7/ Conclusion

In this section we have outlined several data formats, the information that may be extracted from them, and their application toward obstacle detection. We have not considered another processing possibility - the tracking of moving objects. Another problem, the distinction between dangerous and harmless obstacles, is not soluble from examination of the data, and it must therefore be assumed that all obstacles are potentially dangerous.

5.8/ References

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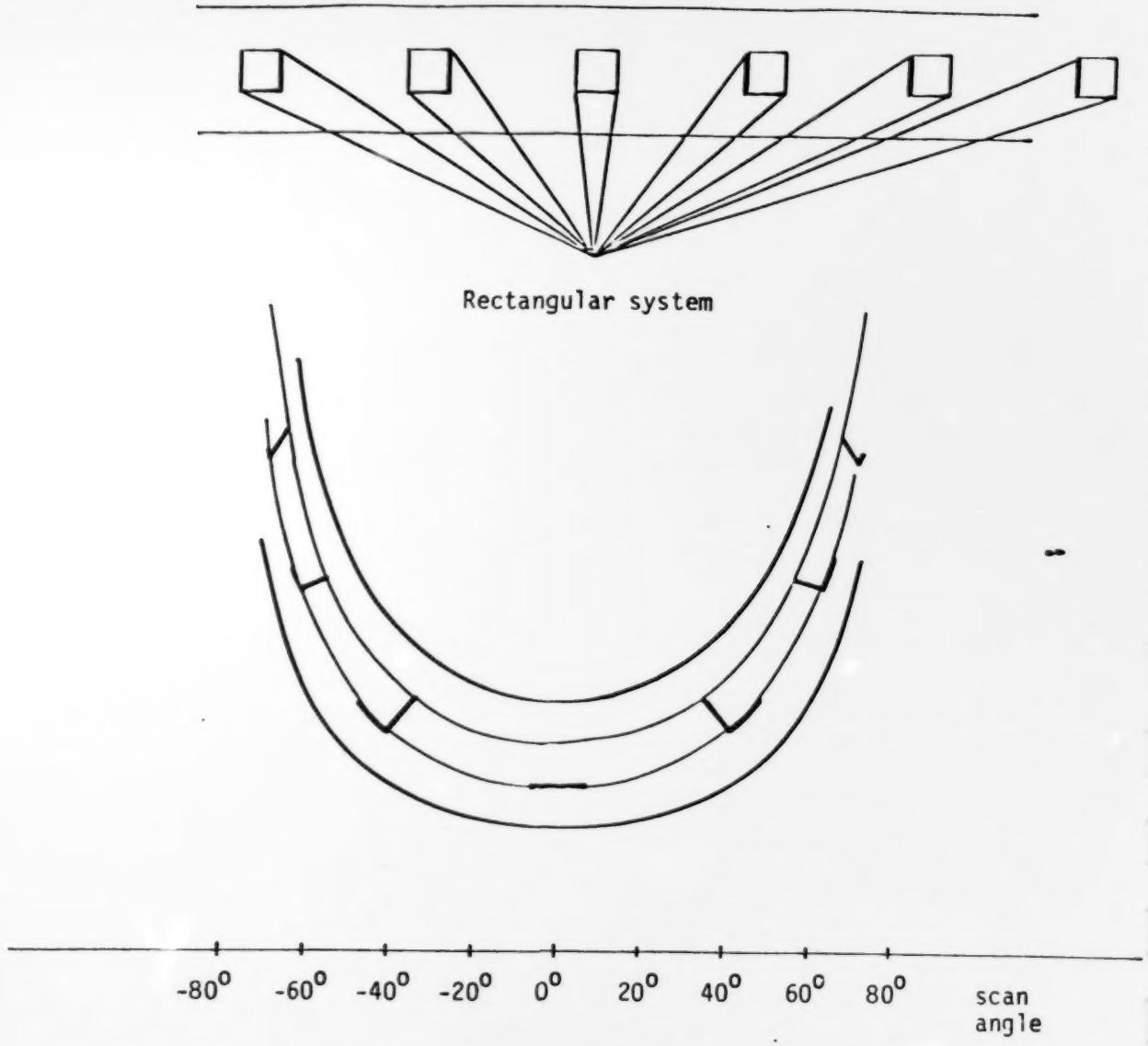


Figure 5.1/ Relationship Between Rectangular and Polar Co-Ordinate System, Applied to Guideway Surveillance

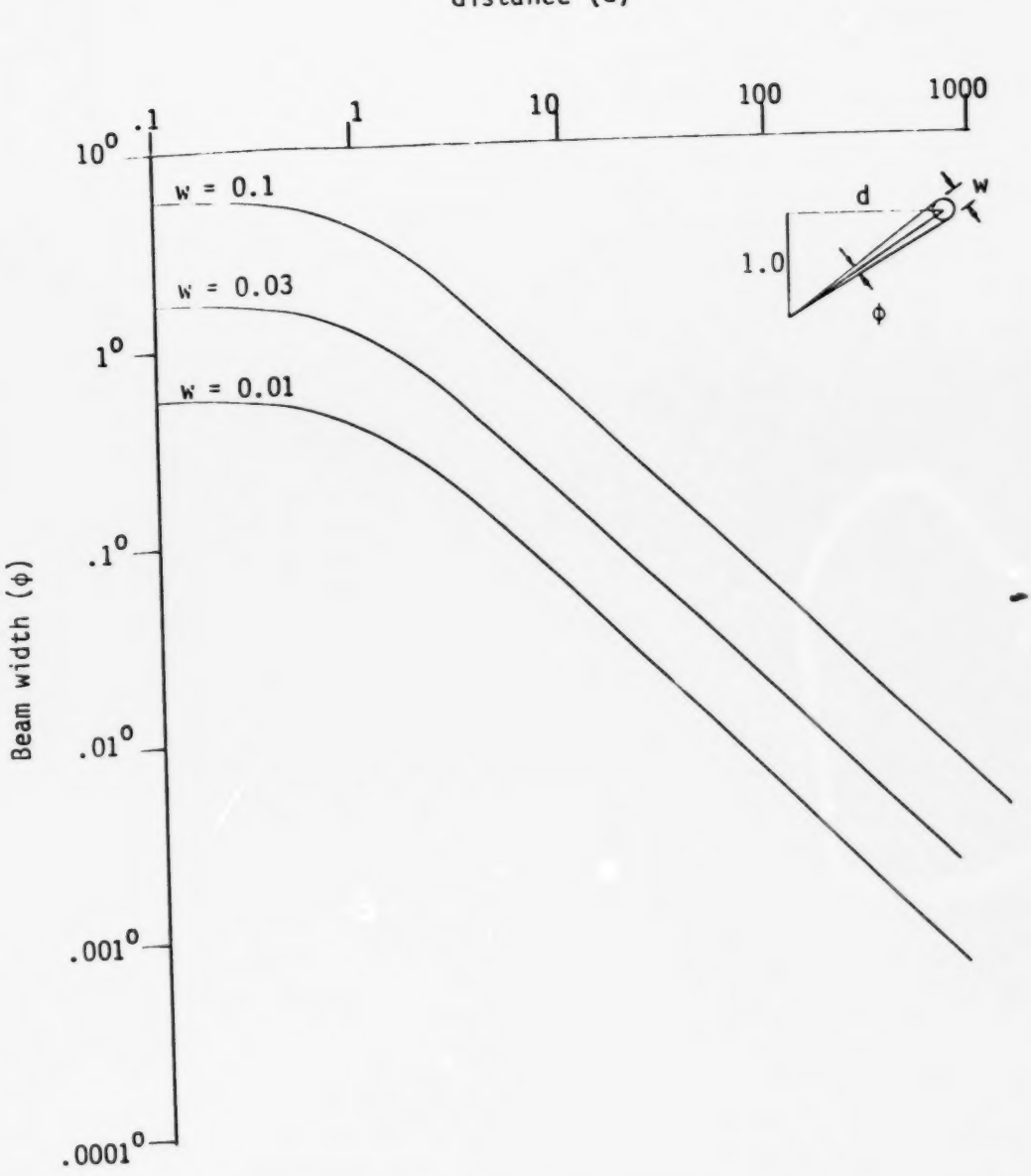


Figure 5.2/ Beam width as a Function of Distance from Scanner (d) and Object Diameter (w) with Lengths Normalized with Respect to Scanner Distance Guideway

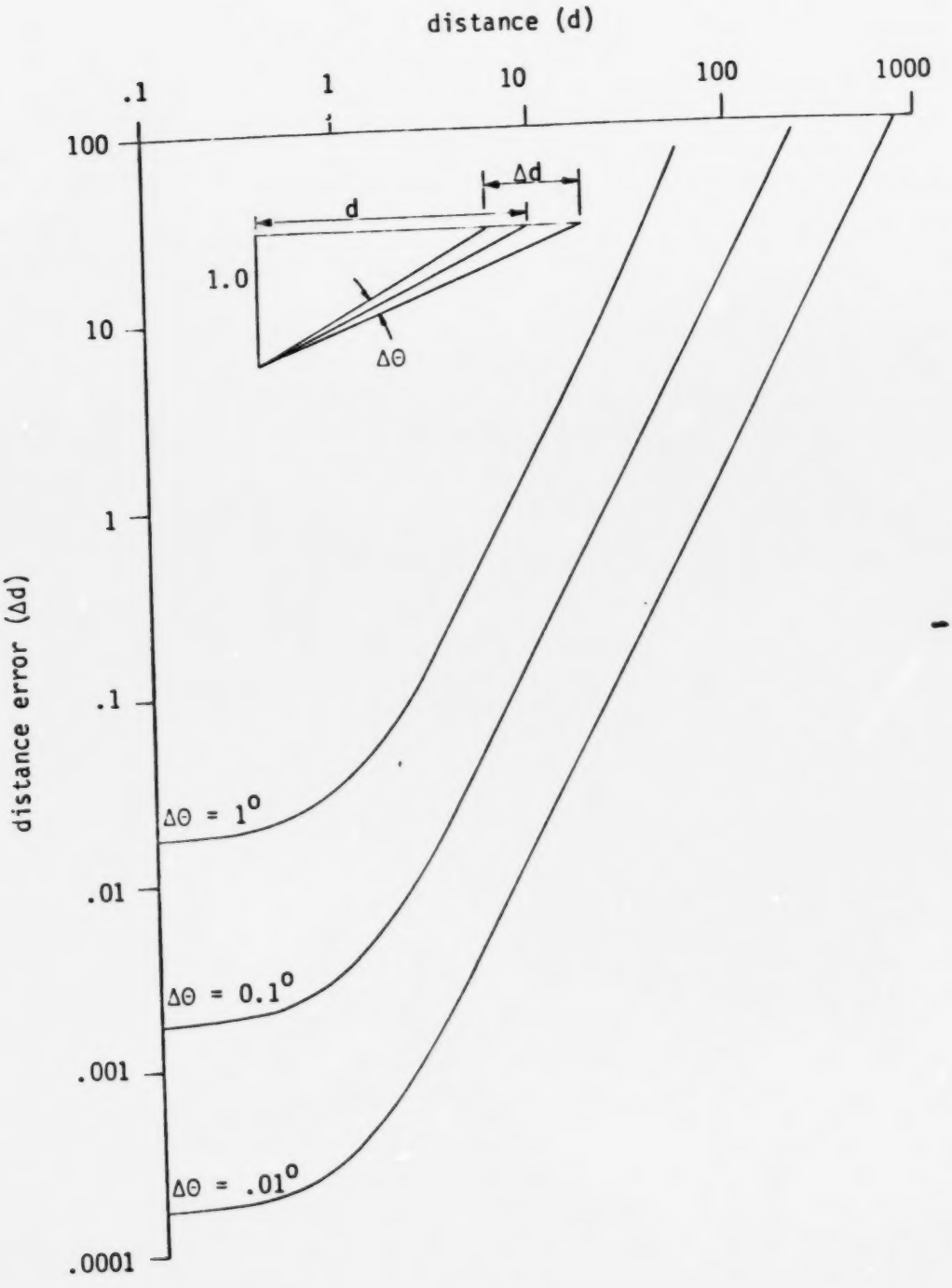


Figure 5.3/ Effect of Inaccuracy of Beam Position and Distance from Scanner (d), with Lengths Normalized with Respect to Scanner Height

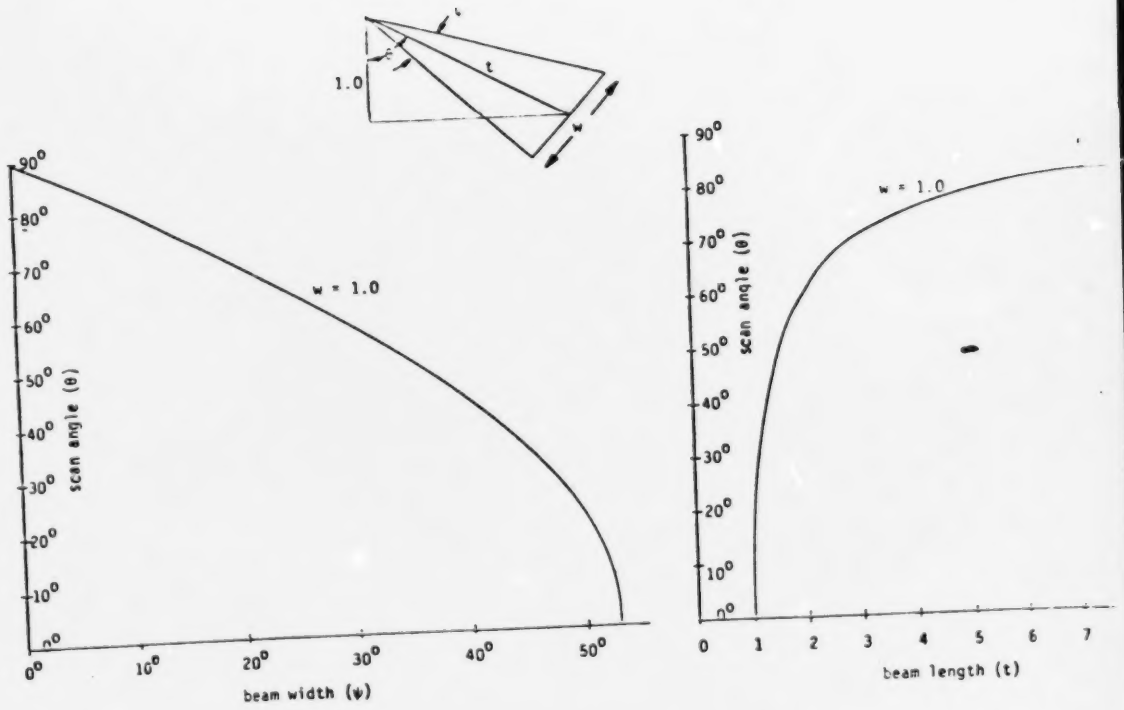


Figure 5.4/ Expected Range Data for Guideway

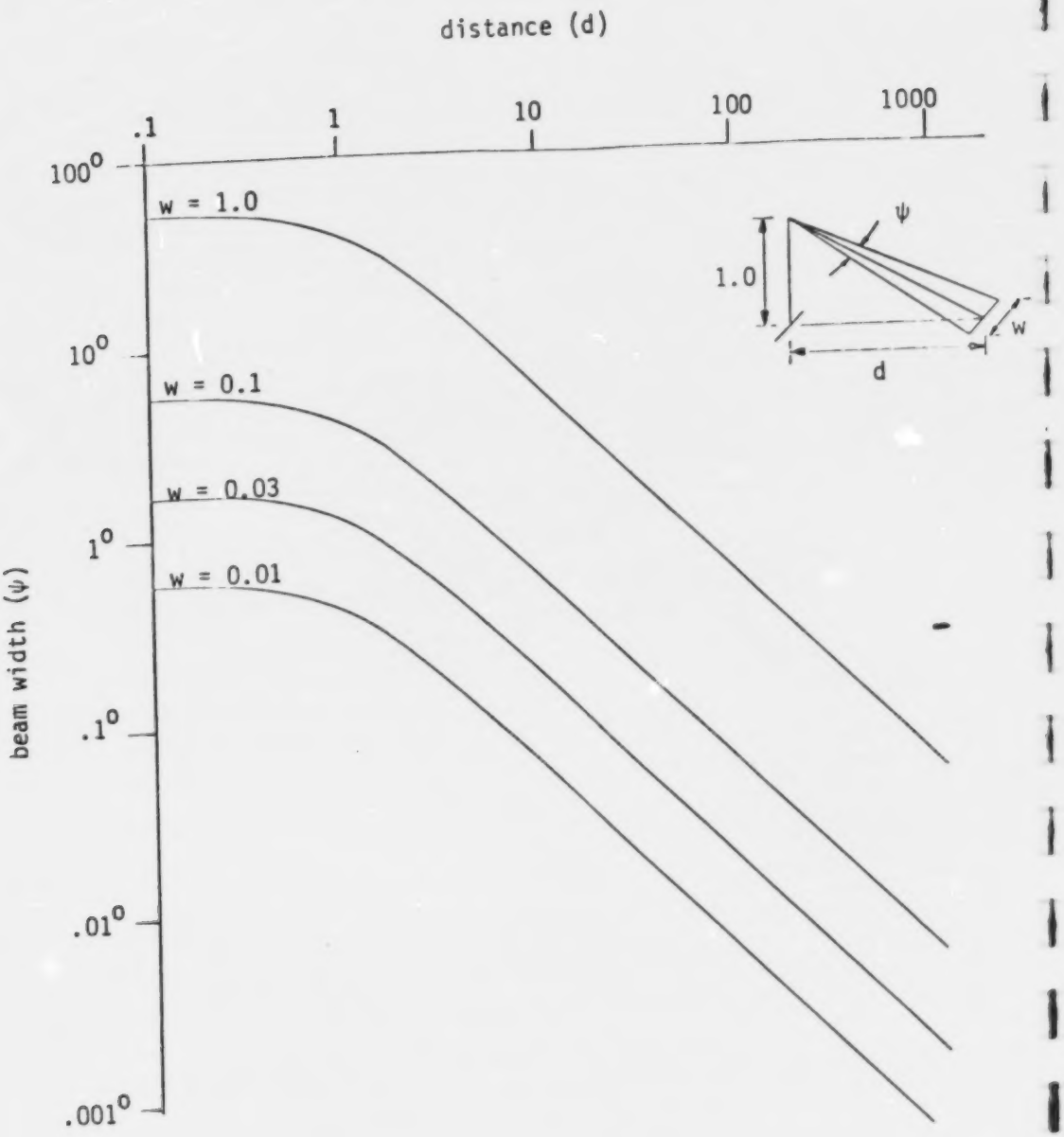


Figure 5.5/ Beam Width Angle as Functions of Distance from Scanner and Guideway Width, With Lengths Normalized with Respect to Scanner Height

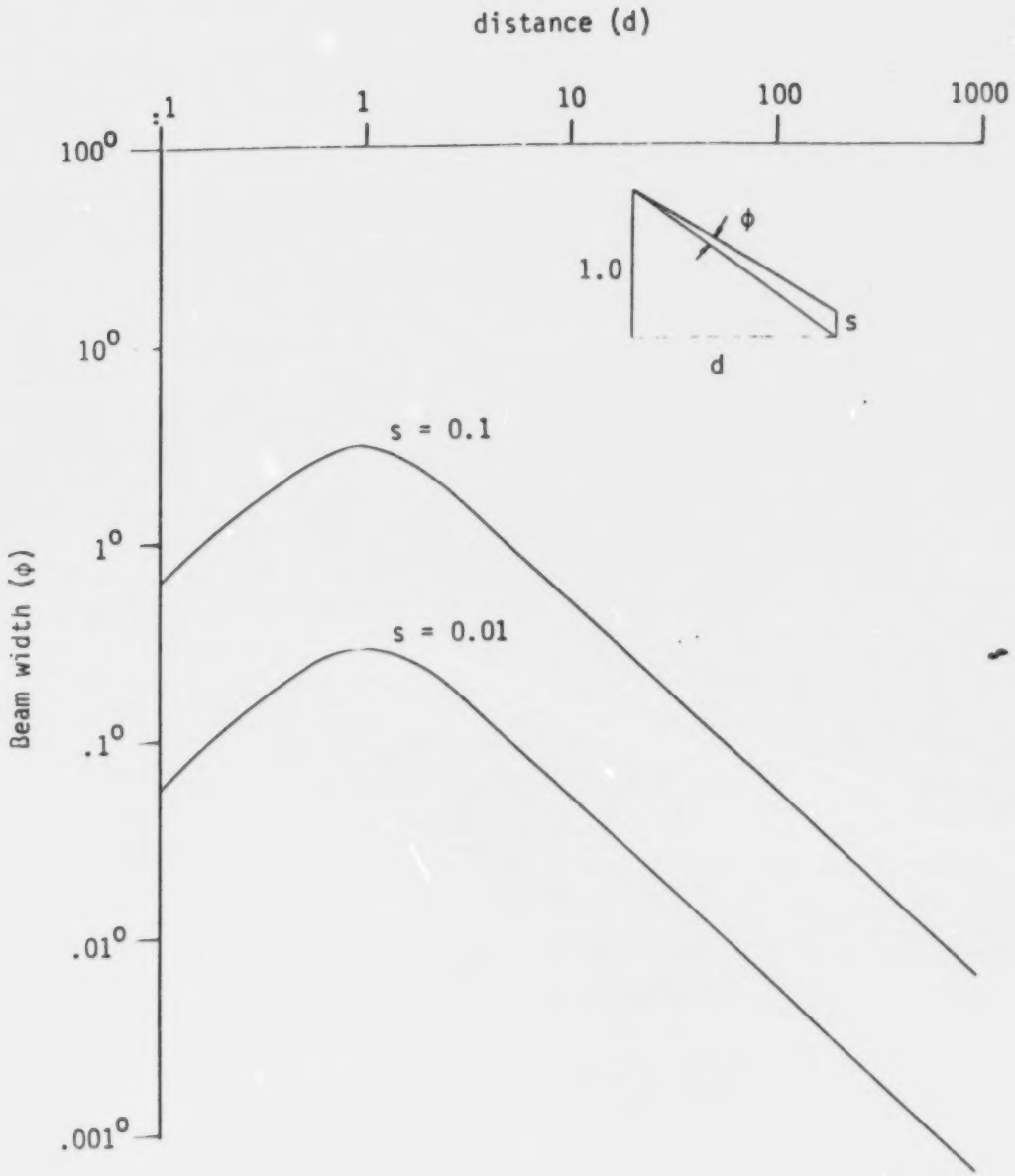


Figure 5.6/ Vertical Beam Width Required to Resolve Obstacle of Height s at Distance from Scanner d, s and d Normalized with Respect to Scanner Height

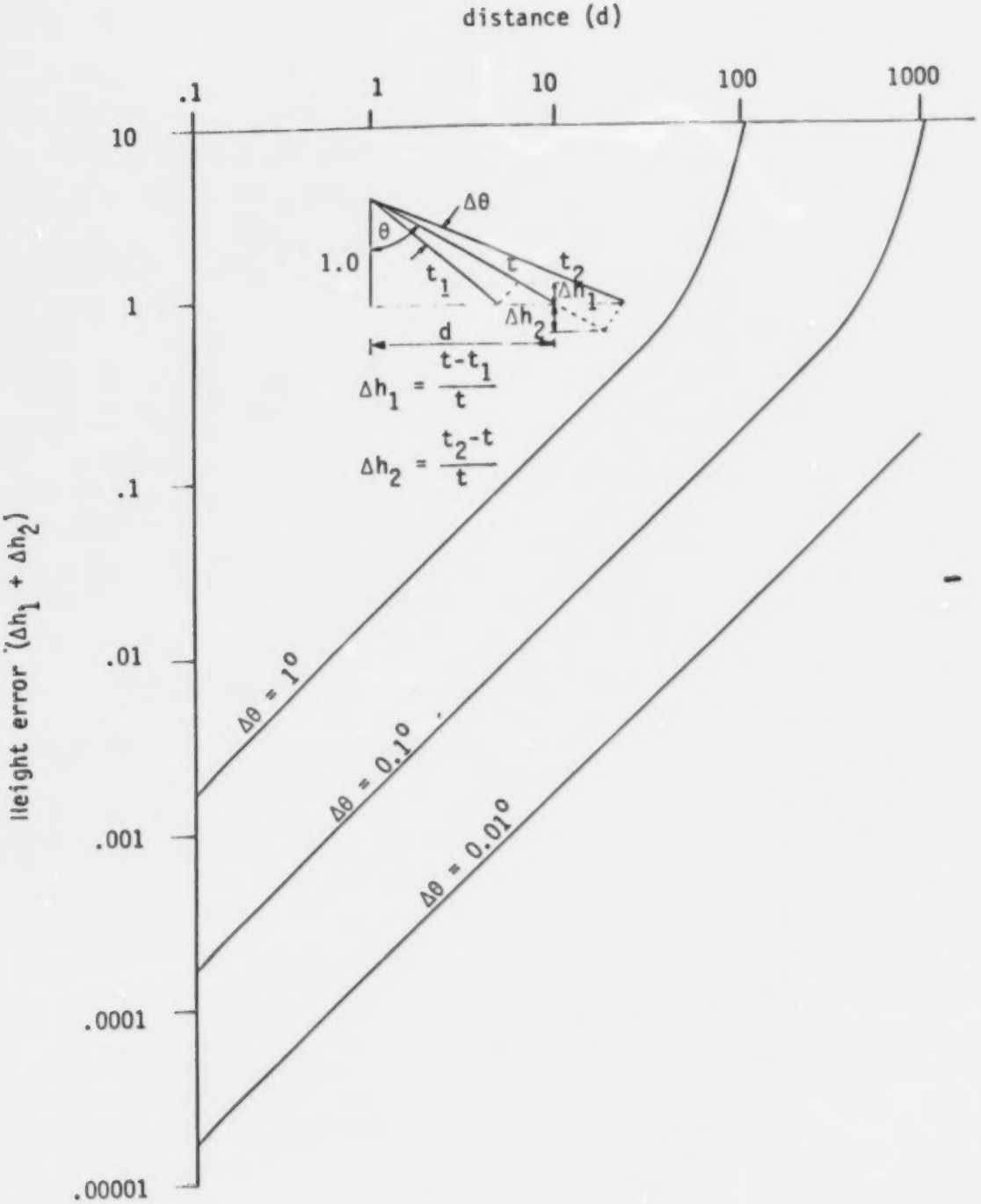


Figure 5.7/ Height Determination Error as a Function of Beam Angle Error and Distance from Scanner, with Lengths Normalized with Respect to Scanner Height

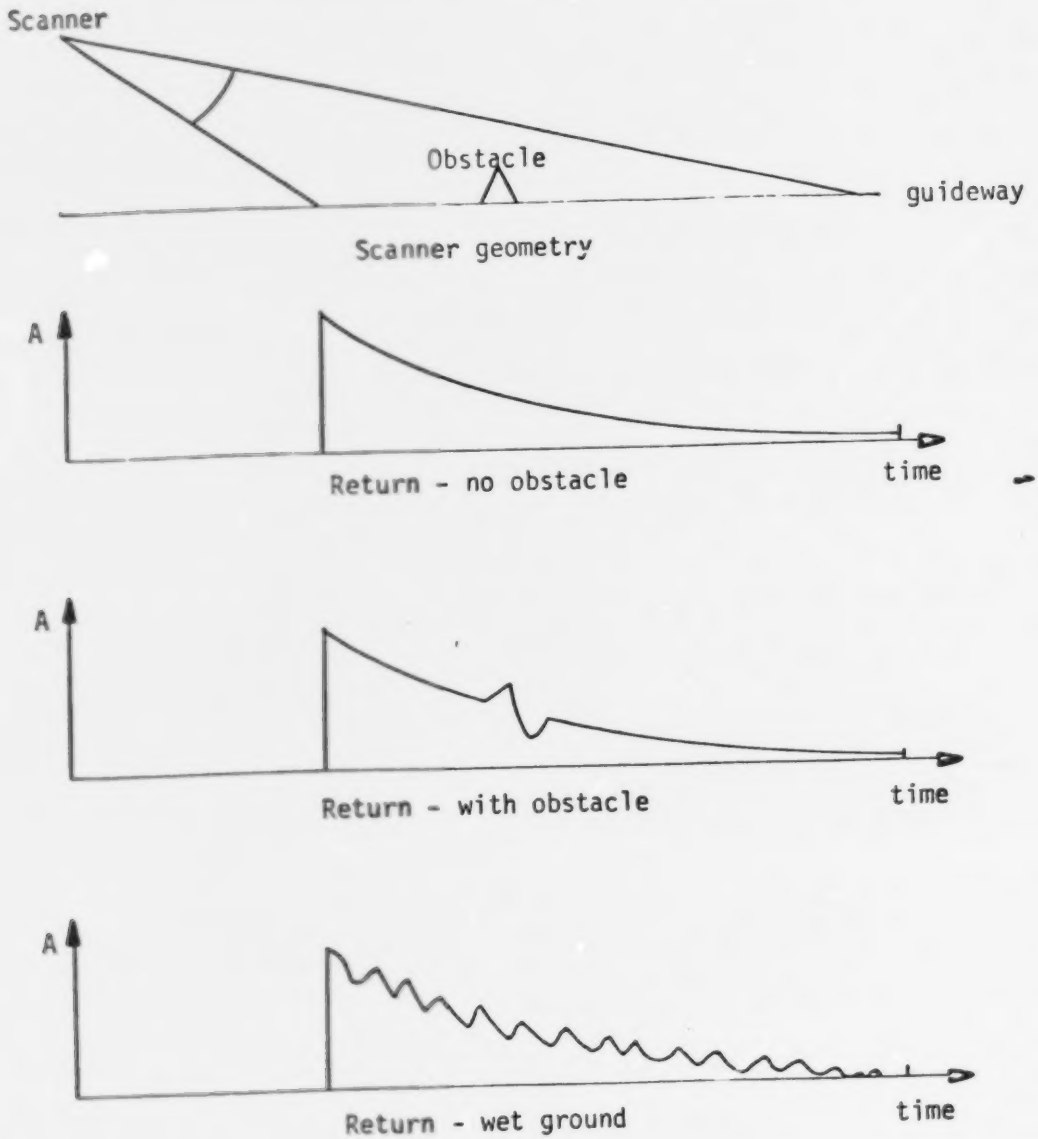


Figure 5.8/ Longitudinal Beam Scan

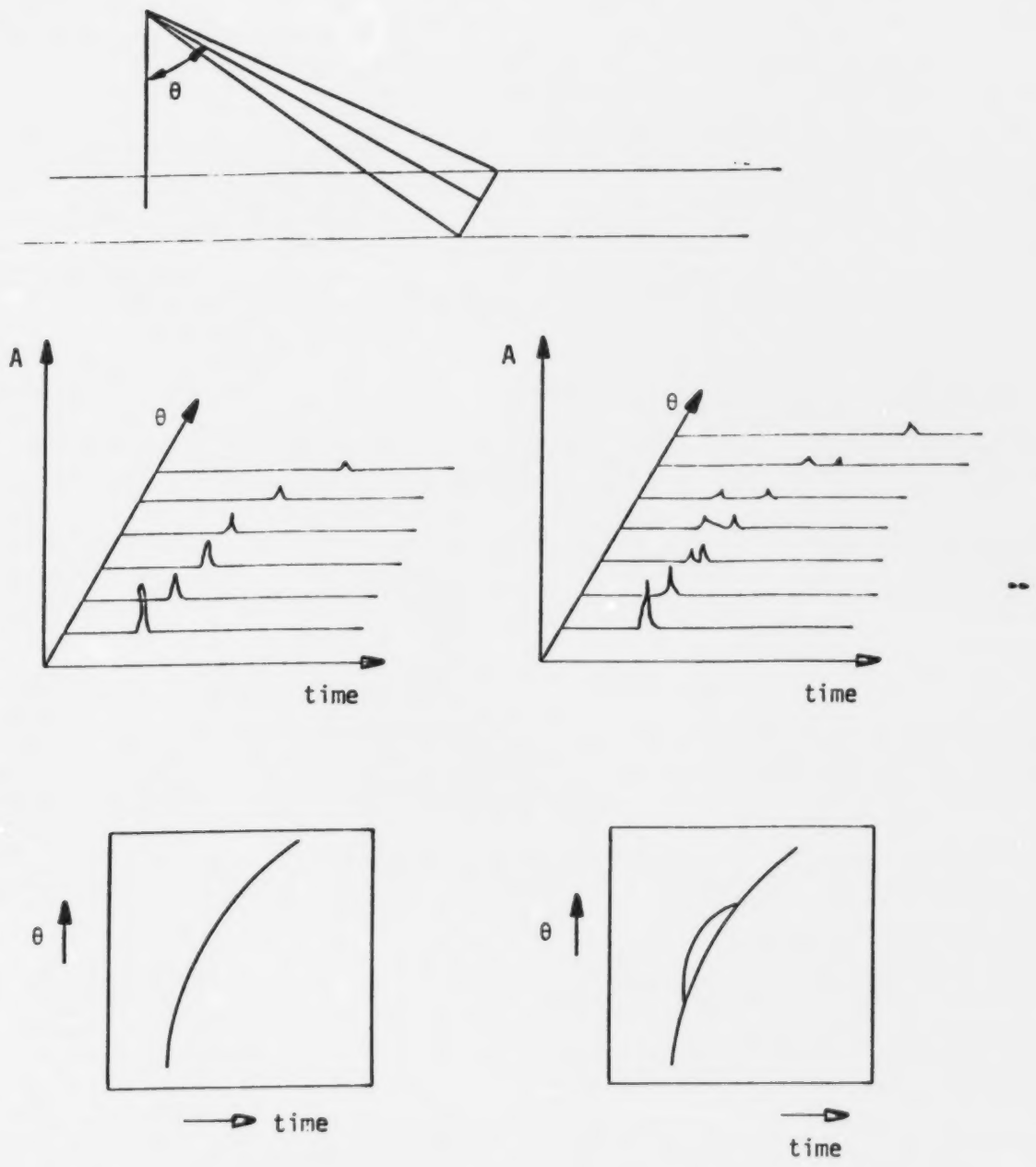


Figure 5.9/ Simple Transverse Beam Scan

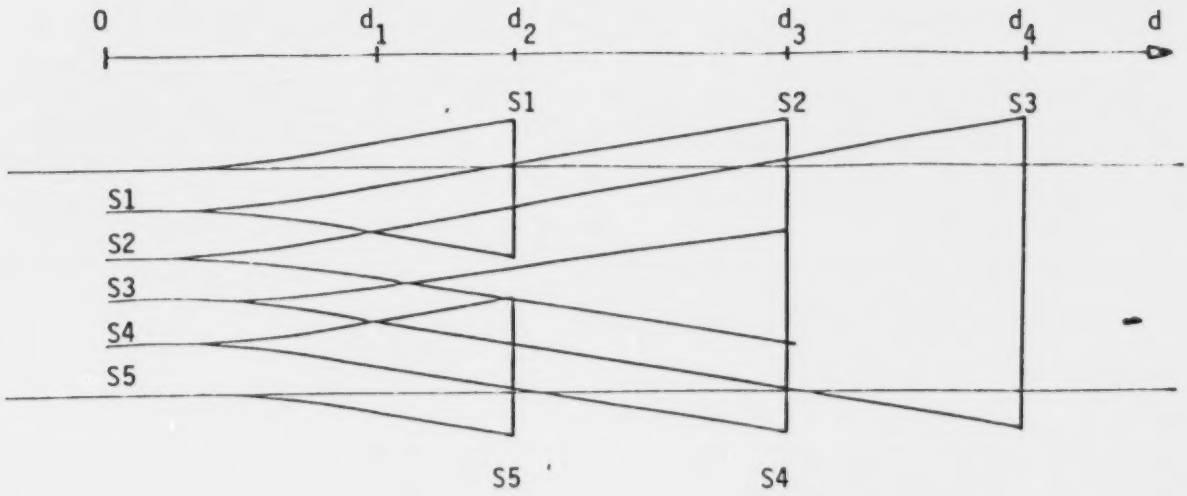


Figure 5.10/ A 5 Scanner Survey of Guideway with the Scanning Pattern of Each Scanner Superimposed on the Guideway

6/ CONCLUSIONS AND RECOMMENDATIONS

6.1/ Conclusions

6.1.1/ General Discussion

The preceding sections have described the principles of various types of active vision sensor and summarized the present state-of-the-art and the effects of atmospheric and environmental factors on the use of these devices. The devices discussed can be broadly classified under the headings of ultrasonic sensors, microwave radar sensors (including millimeter wave sensors), and laser sensors.

Not surprisingly, no one device is pre-eminent for all applications. Sonar (ultrasonic) devices are limited to relatively short-range applications and are subject to disturbances due to atmospheric inhomogeneities. It is felt that they are not suitable for applications requiring moderate to large ranges (over 10 metres) or those exposed to outdoor all-weather conditions. Thus, they are not suitable for any of the four obstacle detection and identification applications discussed in the introduction. They may have applications in the robot guidance and control area. However, here, the problem is that the requirements of robot vision cannot be defined sufficiently closely until the actual robot application itself is defined more closely. It can only be said that ultrasonic sensors are effective for distance measurement tasks in the range of a few centimeters to a few meters. Current sensors are lacking in directivity, but improvement in this area is possible given the impetus of a genuine requirement.

Microwave sensors constitute the most richly developed technology of those explored. Detection and signal processing techniques are highly developed, and some of the achievements in long distance imagery are very impressive. Unfortunately, those techniques which provide the highest resolution, without the use of millimeter wavelengths, require special conditions not met by our situations. Work in the area which is most closely related to our requirement, battlefield surveillance using millimeter waves, is still in its infancy, particularly the field of millimeter wave imaging. It is clear, however, that for the obstacle detection applications, wavelengths below two millimeters are unsuitable because of the effects of clear air atmospheric absorption. (The situation only improves at wavelengths shorter than 30-40 micrometers). Inclement weather adds to the problem but is not the main consideration. Both problems increase rapidly with increasing detection range.

Even with millimeter wave radars, although object detection should be possible for fairly small objects, the resolution available will not be good enough to provide good probabilities of identification of any but large sized objects, e.g. trucks. Identification would have to be based on echo magnitude, and on target outline, if the object were large enough in dimensions.

Millimeter wave radar would seem to be a good possibility for a vehicle borne detector of objects on the guideway for distances of the order of three kilometers ahead of the vehicle. For along-the-guideway surveillance, it would also be a possibility,

but since short range detection is a problem with radar, an overlapping coverage might be necessary. This would make it less competitive economically. The problem with short ranges is due to the difficulty in getting very short pulses (less than 10 nanoseconds) with adequately high power for radars which are also required to detect targets at moderate ranges. No work seems to have been done on very low power radar with very short, moderately low power pulses, designed for a very short (say 50 metre) maximum range. If such radars proved practicable, they might find an application in level crossing surveillance, or for the in-station application. The advantages of millimeter wave devices in these applications, would lie in the higher sensitivity of the detectors possible at these wavelengths, compared to the infrared devices with which they would be competing.

It should be mentioned that FM-CW radars do have the possibility of good short range detection capability, since solid state oscillators can be frequency modulated over wide bandwidths at very high rates. However, they are not very well suited for multiple target situations, being best at determining the distance to the closest large target illuminated by the beam. Nevertheless, their simplicity might make them useful in uses such as level-crossing surveillance.

Microwave radar techniques do not seem to have much to offer for robotic guidance, except perhaps the very short range radars suggested above. Again, however, we must say that more details of the exact nature of the robotic application are necessary to make

a good judgment of the applicability of various techniques.

Laser radar sensors have the advantage of high angular resolution (small spot size) and, at the appropriate wavelengths, e.g. 10 micrometers (10 microns), favorable atmospheric and precipitation attenuation factors, except possibly for dense fog. The data available on attenuation of 10 micrometer radiation by fog from various sources is inconsistent.

Infrared laser radar sensors, therefore, seem competitive in performance with millimeter wave radar. Very short, relatively high power pulses at high repetition rates are achievable. Using heterodyne detection techniques, similar, in principle, to those used in radio communications and radar, the detection sensitivity for infrared echoes is comparable to that achieved with microwave radar.

Looking again at the possible applications we discussed in the introduction, let us examine what appear to be the most suitable system, or systems, for each of these applications based on this study.

6.1.2/ Vehicle Mounted Sensor System

Consider first obstacle detection by means of a sensor system mounted on the front of the vehicle, scanning the guideway in front for a distance of approximately 0.5 - 1.0 kilometres. If effective, this may be the least expensive solution to the obstacle detection problem, depending on the number of individual vehicles in service, since it minimized the number of installations and avoids problems of servicing equipment in remote locations. For this application,

there appear to be two candidates.

One is a millimeter wave radar (3 mm) with as large an antenna as practical, possibly focussed at a distance of 500 m or 1 kilometre (there is little experience with focussed radar antennas) to reduce spot size at that distance. The peak power would be 1 Kw with a pulse width of 10-20 nanoseconds and a pulse repetition rate of 10-20 kHz. This is an average radiated power of 0.1 - 0.4 watts. The peak power of 1 kilowatt might be achieved either by direct means (generating the short pulse directly from a higher power klystron tube) or by using a «pulse compression» circuit in which the transmitted power is generated in a longer coded stream of short segments of lower power. This might consist, for instance, of a series of about 250 ten nanosecond segments of 4 watts power level. The echo is compressed, on reception, into the equivalent of one high power ten nanosecond pulse, by means of the special coding of the pulse. This approach would allow the use of a solid state generator in place of the klystron, avoid the high voltates (21 kV) used in the klystron, and would be more compact. In production, it would probably also be less costly. The pulse compression approach would obscure echoes from the first 375 metres in front of the vehicle, so it would have to be backed up by a short range system for low speeds or starting up. Data sheets for a klystron transmitter subsystem meeting the above requirements for direct generation of short high power pulses are given in the Appendix.

There would be little advantage in scanning with this system since, at best, the beam would be almost as wide as the

guideway. (This is not really an imaging system, then.) A two horn feed might be used to produce two partly overlapping beams. This would widen the overall coverage and comparison of the signals in the two beams would indicate whether the target was to the right or left of centre. Two, somewhat smaller antennas, one on the left and the other on the right side of the front of the vehicle, might be used to improve the full coverage of the guideway at intermediate distances.

The second candidate for the vehicle mounted obstacle detection system is a 10 micrometer (10 micron) infrared CO_2 laser radar. This might use a 0.1 antenna and have a 7×10^{-3}° beamwidth. Its spot size would be about 0.15 m at 500 m and 0.20 m at 1 km, so it would be capable of crude imaging. Using a simple TEA laser the pulse width would be 50-100 nanoseconds, the peak power 200-500 kw watts, and the pulse repetition frequency (prf) a few Hz. The repetition rate could be increased but only if the pulse width is increased. To achieve a higher prf it would be necessary to use a Q-switched laser which might have the following characteristics: pulse widths of a few hundred ns and peak powers of up to a kilowatt with repetition rates of a few kHz. The complexity of a Q-switched system at present would appear to be much greater than that of the TEA laser but with available technologies custom systems may be designed for the particular applications described.

The scan would cover ± 0.25°, i.e. 4.36 m width at 500 m, or 26 m width at 3 km, and would cover three levels vertically to provide some height information in the image.

6.1.3/ Along-The-Guideway Surveillance Sensors

For the along-the-guideway surveillance application the proposed system is a 10 micrometer laser scanning a length of 500 m of the guideway from a position above the guideway. See Figure 6-1. The beam scanned is narrow in the direction along the guideway and somewhat wider across the guideway. The scanner would be mounted at least 15 m above the guideway.

We must distinguish two situations in analysing the behaviour of this type of system. The first is that in which the laser beam forming reflector (antenna) is amall enough that the near field conditions do not extend substantially more than 15 metres. This would be true for reflector sizes of less than about 2 cm.

For this case, considering scanning over the ± 250 m length of the guideway covered, since the distance is varying and the beam has a constant angular width, the «footprint» of the beam on the ground will normally vary as the beam scans from one extreme of the length of guideway covered, through the vertical position to the other end of the coverage. See Figure 6-2. The feature of this which would cause some concern is that if the beam size is chosen so that it covers approximately the width of the guideway at the extremes of the section of guideway covered,at the middle when directed straight down the beam would cover only a small portion of the guideway width. One way around this would be to use more than one beam, side by side, across the guideway. Another would be to use a beam with specially shaped shoulders so that the detection contours on the ground would be

the width of the guideway at all distances. See Figure 6-3.

The second situation is that in which the antenna is so large that the near field conditions extend out essentially to the full distance scanned. In this situation the across-the-guideway width of the «footprint» would be more or less constant everywhere and approximately equal to the width of the antenna itself. In this situation transverse scanning, also, would be necessary to cover the guideway width (or an array of beams might be used).

In between these two extremes there is a variety of intermediate conditions.

The characteristics of the 10 micron laser radar system suggested for this application would be similar to those described for the vehicle-mounted system.

One reason for preferring the above-track mounting is that it is the only exposed mounting which is reasonably free of problems from accumulation of snow and ice and dirt if it is covered by a small leak proof hood or roof. See Figure 6-4.

6.1.4/ Level Crossing and In-Station Surveillance

The same basic system is recommended for the level crossing surveillance and in-station surveillance applications, although in the latter case the limitations found in other locations due to snow and ice do not apply. Because the maximum range in the level crossing situation is less than in the along-the-guideway applications, the antenna reflector size could be reduced, for the same minimum detection sensitivity, and it might be desirable

to modify the scan pattern to optimize the coverage of the smaller area.

6.1.5/ Short Comings in the State-of-the-Art

It should be pointed out that complete systems do not exist to do exactly what is required for any of the above applications, although some sub-systems of potential use have been identified. In all cases, custom built equipment would be required, and in some cases there would be development necessary. It will also be essential to gather information on the behaviour of targets of interest in these applications at millimeter wave frequencies and at laser frequencies. Without this information, many of the conclusions of a study such as this are purely speculative. Another area in which experimental clarification would be valuable, is the effect of fog on laser radar at 10 micrometers (microns) wavelength. Existing information on attenuation of 10 micrometer radiation by fog is inconsistent and the resolution of the inconsistency is necessary to determine whether millimeter wave radar is more advantageous for some of our uses than 10 micrometer infrared laser.

6.1.6/ Robotic Guidance

Turning to the question of sensors for robotic guidance and control, it is not possible to make any specific suggestions until a more specific requirement is available. Conventional pulse radar systems are not appropriate because they have short range limitations, due to their relatively long pulse widths. FM-CW radar systems might be useful for range determination since solid state millimeter

wave generators can be swept rapidly over large bandwidths making measurement of short distances feasible. A limitation common to all microwave and millimeter wave systems for short rang applications is that near field transverse resolution is limited to, approximately, the size of the antenna, so we either have wide angular beamwidth or large illumination spot size. At infrared (laser) wavelengths this limitation disappears and, with low power lasers, it is possible to get short pulse widths and high repetition rates, a necessary condition for short range measurement and imaging. Such lasers have been used in experiments aimed at robotic guidance applications. Infrared triangulation seems to offer possibilities of an inexpensive range determination system for short ranges, which can be combined with an imaging capability. This seems promising for robotic guidance.

6.2/ Recommended Future Program

Based on the considerations discussed above, we feel that the most promising system for further study is a vehicle mounted system based on the CO_2 laser (at 10.6 μ). A vehicle mounted system is likely to be the most cost effective and will minimize maintenance problems in the field. The laser system offers higher resolution than the millimeter wave system, with considerably smaller antennas. The 10.6 micrometer wavelength shows less atmospheric attenuation and as good performance in rain, snow and, probably, fog, as the millimeter wave systems. The system would be designed for ranges up to 500 to 1500 metres. Such a system can be designed, built and tested in three or four years. If it is proven successful, a finished product can be made available after suitable

optimization within the next two to four years if the users show active interest.

We propose the following phased program leading to its development to the stage suitable for field evaluation.

Phase I

In this phase a detailed design of the system will be undertaken which will identify all the components and subsystem necessary to build the complete package. This will include the laser and its optical antenna configuration, the signal detection system, the processing requirements, the packaging requirements suitable for mounting the system on the vehicle.

A six month effort will be required to perform this phase. The cost in performing this phase will be about $25,000 (est). This phase will also provide a detailed costing for a follow-on program for building such a system (Phase II).

Phase II

In this phase, a complete system will be built, based on the design performed in Phase I. A time frame between 1 to 1-1/2 years is expected to perform this phase.

Phase III

In this phase, the system built will be field tested (logistics of this is to be negotiated later) on a suitable vehicle and track.

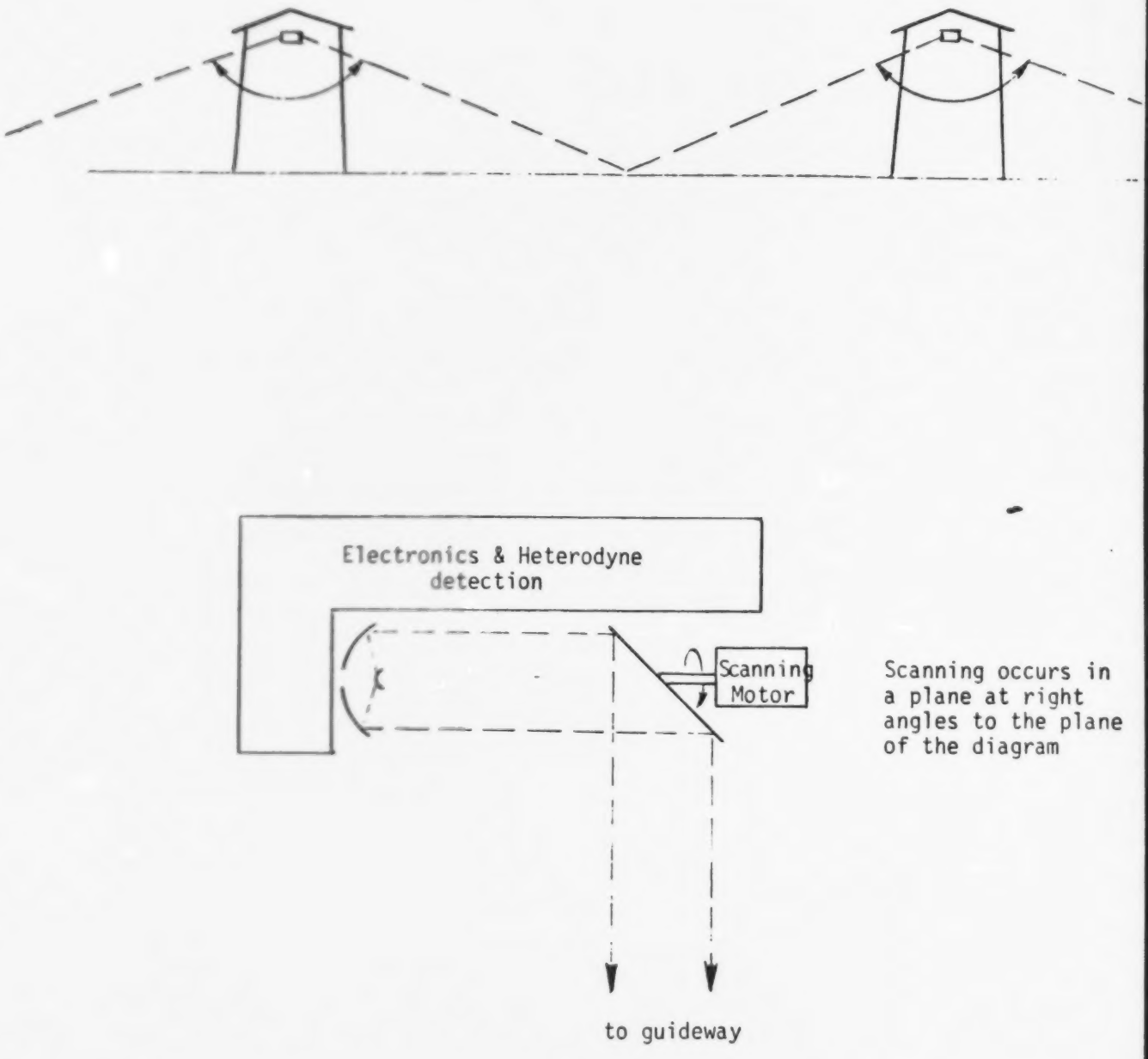


Figure 6.1/ Overtrack Surveillance Scanner Using 10 Micrometre Laser

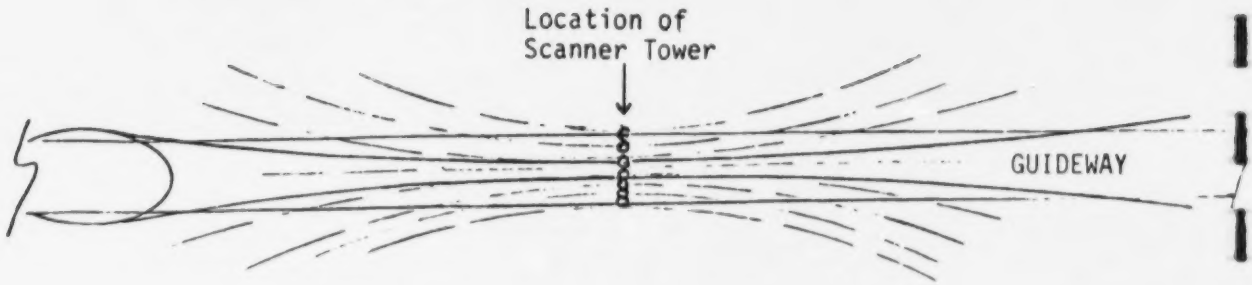
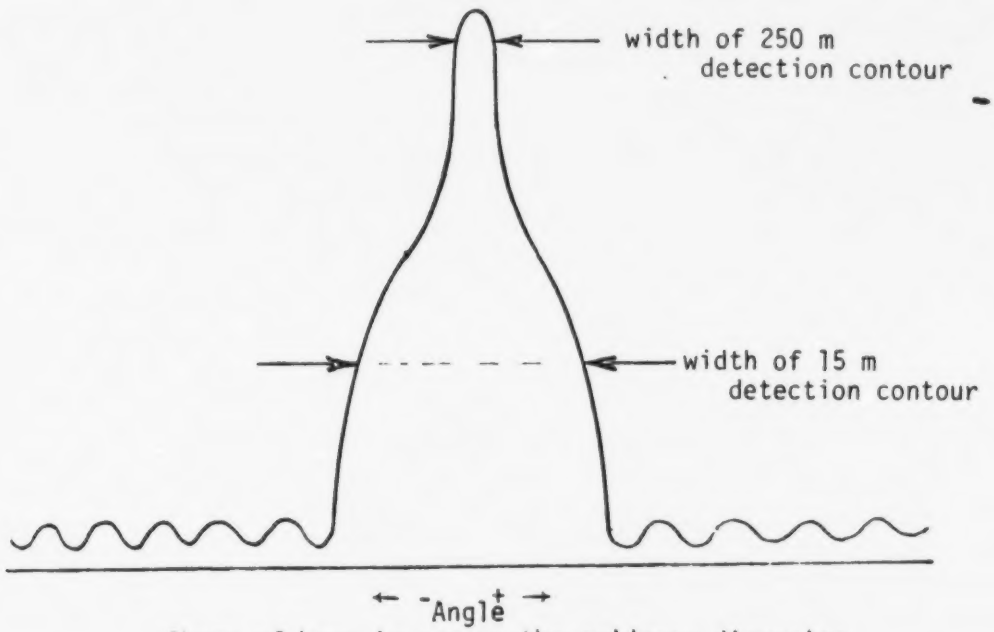


Figure6.2/ Variations of Width Covered as Beam Scans Along Guideway



Shape of beam in across-the-guideway dimension

Figure 6.3/ Beam Shaped to Main Constant Width Detection Contour

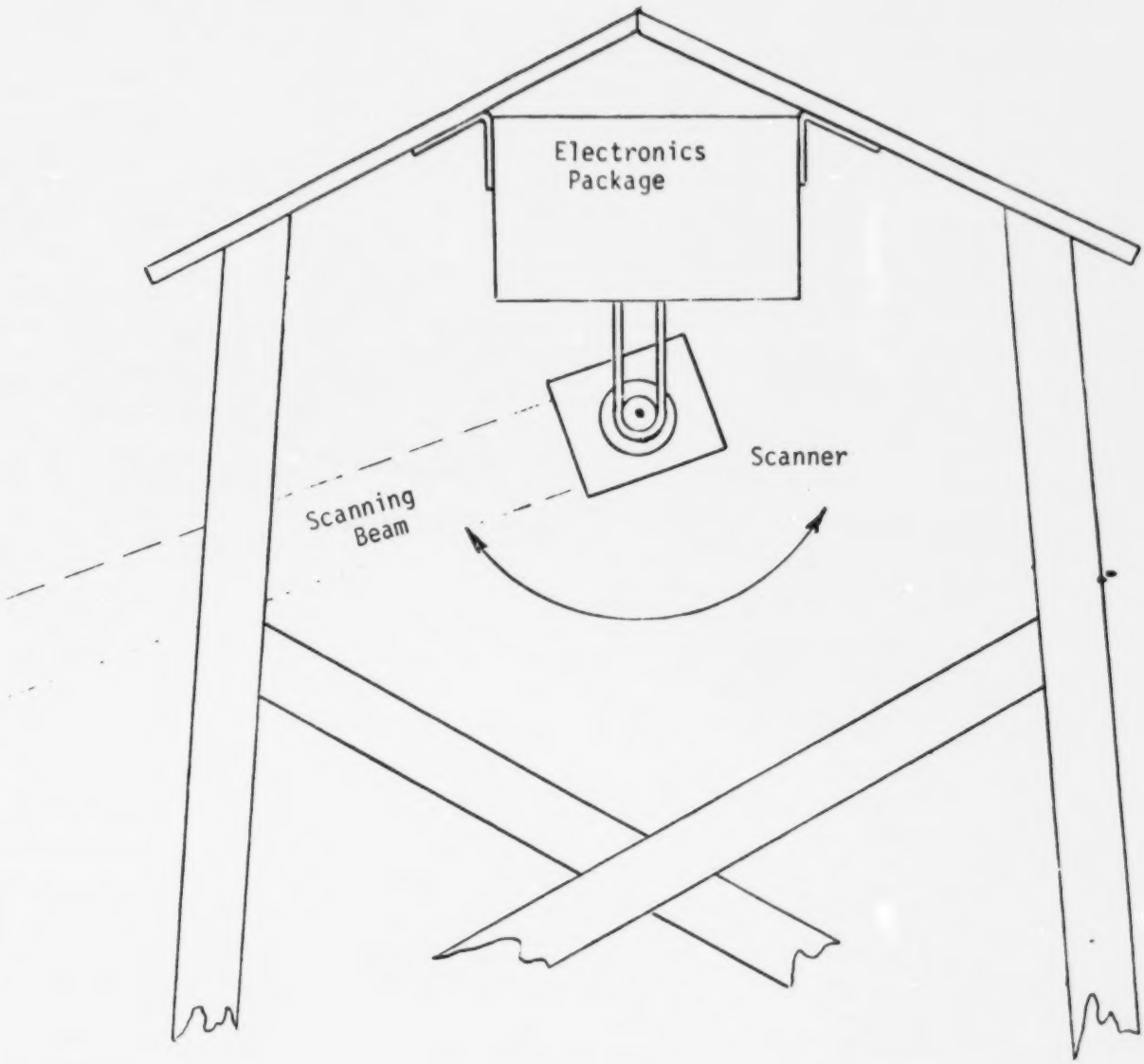


Figure 6.4/ Scanner Shelter